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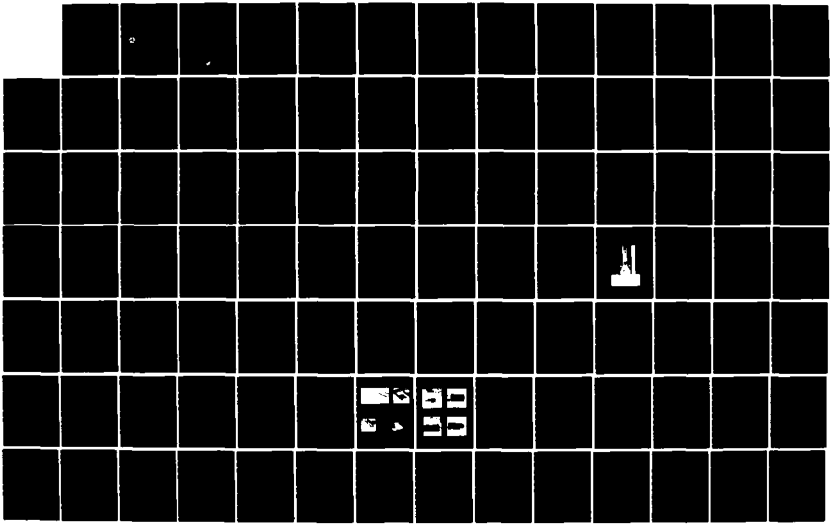

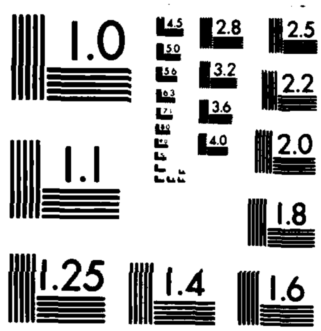

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THE DESIGN AND MODEL TESTING OF A COLLISION TOLERANT PILE STRUCTURE

AD-A155 485

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&

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FINAL REPORT
MARCH 1985

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16. Abstract

A Collision Tolerant Pile Structure (CTPS) for deploying navigation aids was developed having the ability to sustain collision by barge traffic. The CTPS concept consists of the aid itself mounted at the top of a pile which is hinged at the mudline. The hinge is omnidirectional, possesses complete downwards articulation, and provides a restoring moment to return the structure to the vertical position.

To serve as a design tool, computer programs were developed for simulating pile dynamics during operating, hurricane and collision conditions. Using preliminary computer model results, several hinge concepts were developed and evaluated, and a central universal joint, peripheral stay arrangement was determined to be the best system. A design based on this concept was developed, and a physical scale (1/15) model was built for testing.

Initial experiments were conducted out of water to evaluate hinge stiffness characteristics, then uniform current tests were conducted at the Coast Guard Academy's circulating water channel. Results from both experiments indicate that the CTPS has sufficient stiffness to remain nearly vertical during operating conditions. Collision experiments carried out at the UNH indoor pool showed that the pile can endure barge collisions. A final computer model simulation showed that the CTPS design presented here should be successful.

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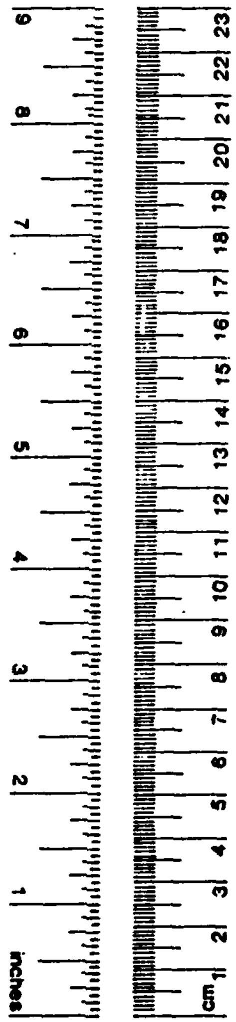
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

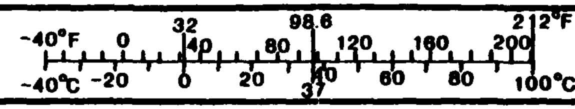
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ABSTRACT

A Collision Tolerant Pile Structure (CTPS) for deploying navigation aids in shallow water was developed having the ability to sustain collisions by barge traffic. The CTPS concept considered consists of the aid itself mounted at the top of a rigid pile which is hinged just above the mudline. The hinge is omni-directional and allows the pile to fold down in the event of a collision. The hinge also provides a restoring moment to return the structure to the vertical position.

The CTPS was designed to meet Coast Guard criteria. The pile inclination angle must be small (5 deg as a design goal, 10 deg maximum) during extreme operating conditions (specified as 30 ft depth, 3 kts current, 60 kts wind and 5 ft waves). The system must survive hurricane conditions (that is, 9 ft of storm surge, 100 kts winds and 6 ft waves). The CTPS is required to sustain impact by a barge moving at 10 kts, and it is desired that the mudline clearance be as low as 3 ft. The CTPS installation must be similar to existing practice, and cost must be low ($5,000 as a design goal, $10,000 maximum).

To serve as a design tool, computer programs were developed for simulating pile dynamics under the conditions referred to in the design specifications. Separate programs were written for operating, hurricane and collision conditions and for the recovery process. The CTPS was modeled as a mass-rigid bar-hinge system with loadings and resulting motion confined to a vertical plane. Wind is considered steady; wave activity is represented by a regular, sinusoidal wave, and current is taken to be steady and uniform with depth. During the collision process the barge is assumed to maintain constant speed. In use, design and environmental parameters are input, and the program calculates the response time series.

Using preliminary computer model results for guidance, the hinge component was developed. Several hinge concepts were evaluated, and a central universal joint, peripheral stay arrangement was determined to be the only satisfactory system. A major feature of this concept is the use of a single, pre-stressed spring, housed within the pile (made of pipe), to tension the stays. A design based on this concept was developed, and a physical scale (1/15) model was built for testing.

Initial experiments were conducted out of water to determine the hinge stiffness characteristics. These preliminary results indicated that the stiffness is adequate for meeting the verticality requirement and for recovery from a knock-down. Next, tests were conducted at the U.S. Coast Guard Academy's circulating water channel. Here it was found that the scale model CTPS possessed more than sufficient stiffness to meet the verticality requirement at (Froude scaled) maximum current. Hydrodynamic load measurements showed that the drag coefficient was less than one thus justifying the use of unity in the computer simulations. Collision experiments were then carried out in the UNH indoor pool. It was found that the scale model could endure typical barge collisions at the design speed (Froude scaled) and return to the vertical. These observational results were documented by taking movies and photographs. Impact force measurements confirmed that the computer simulations were sufficiently accurate (within 23%) for design purposes.

To estimate full-scale CTPS dynamic response, the computer models were applied to a full scale prototype under the design criteria conditions. It is predicted that the maximum inclination angle restriction (10 deg) can be met and that no damage to the pile and hinge should occur during hurricane conditions. The pile system should survive typical barge (12 ft draft) collisions at maximum speed, but impact loads were found to increase enormously with decrease in

clearance. For this reason and because height is needed for the hinge itself, the 3 ft mudline clearance specification cannot be met.

Logistical considerations were investigated, and procedures for installing the pile using familiar methods were outlined. Cost estimates indicate that the CTPS itself meets the maximum allowable restriction ($10,000) and that CTPS systems should become cost effective after 3 collisions.

Because nearly all the design specifications have been shown to be achievable, it is concluded that the CTPS design should be successful. We therefore recommend that the next step in development be taken in which a full scale prototype is built and field tested.

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NOMENCLATURE

A_b	=	area of boards
A_p	=	projected area of pile
C_a	=	drag coefficient of pile in air
C_b	=	drag coefficient of boards
C_L	=	lift coefficient of pile due to vortex shedding
C_m	=	inertia (added mass) coefficient of pile
C_w	=	drag coefficient of pile in water
d	=	depth to hinge
d_b	=	draft of barge
d_h	=	horizontal distance from bracket to top of pile
d_p	=	diameter of pile
d_{ref}	=	reference distance
d_t	=	total depth
E	=	Young's modulus
F_B	=	barge force on pile
f_b	=	barge freeboard
F_C	=	current force on pile
F_s	=	prestressed spring force
g	=	gravitational constant
H_w	=	wave height
I	=	area moment of inertia
I_H	=	pile system moment of inertia with respect to hinge axis
I_{HT}	=	pile system moment of inertia including added mass effects
k	=	wavenumber
k_1	=	initial stiffness constant
k_2	=	large angle stiffness constant
L	=	barge length

ℓ_b = length from hinge to boards

ℓ_c = length from hinge to point of barge contact

ℓ_m = length from hinge to load mass

ℓ_p = pile length

L_r = scale ratio

ℓ_r = length of rubber hinge section

ℓ_s = submerged length of pile

M = applied moment about hinge axis

M_B = moment exerted by barge

M_c = moment due to relative water movement

M_G = gravitational moment

M_m = applied moment measured in bench tests

M_H = hinge moment

m_ℓ = mass of load

m_p = mass of pile

M_w = wind moment

R_H = horizontal base reaction force

r_i = inside radius of rubber hinge

r_o = outside radius of rubber hinge

r_s = spreader radius

R_V = vertical base reaction force

s = coordinate measured parallel to pile from hinge

T = wave period

t = time

t_i = time immediately before impact

t_f = time immediately after impact

U = velocity scale

U_a = wind speed

U_b = barge speed

U_C = current speed

u_r = water velocity relative to pile

u_w = horizontal component of wave fluid velocity

v_w = vertical component of wave fluid velocity

W_ℓ = weight of load

W_p = weight of pile

x = horizontal coordinate measured from hinge position

y = vertical coordinate measured from the equilibrium surface position

θ = angle of pile with respect to the vertical

θ_b = hinge moment breakpoint angle

θ_c = angle between pile and barge force

θ_f = barge bow angle

λ = wavelength

ρ_a = air density

ρ_w = water density

σ = wave radian frequency

ω_o = pile natural frequency

I. INTRODUCTION

BACKGROUND

Rigid pile structures currently used by the Coast Guard to support aid-to-navigation markers are susceptible to collision by towed barges. Tugs towing barges skirt the edges of narrow channels to avoid deep-draft ocean vessels operating in the main channel. Though the tugs themselves can usually avoid navigation aids on channel boundaries, the barge strings being towed will often hit the navigation aid supporting structure. Considerable expense is involved in locating the lost position, pulling the damaged marker and driving a new pile, as well as purchasing structure components.

This problem can possibly be alleviated by replacing existing rigid pile supports by a compliant Collison Tolerant Pile Structure (CTPS). Miller (1982) provides evidence that this concept is promising and should be developed. This report presents results of a study to develop, analyze and test a CTPS design able to sustain multiple collision without requiring major repairs.

The CTPS concept considered consists of an aid to navigation marker/light mounted on a single pile which is hinged just above the mudline as shown in Fig. 1. The hinge is omnidirectional with respect to barge course and should possess full vertical to horizontal articulation. The hinge must provide a restoring moment to return the pile to the upright position after a knockdown and to maintain a near vertical position while the system is in normal operation. The CTPS system and the hinge component in particular were designed to meet specific performance requirements formulated by the Coast Guard.

DESIGN REQUIREMENTS

The CTPS is to be suitable for use in the port of Houston, TX, an area for which pile destruction is especially serious. Design requirements include the

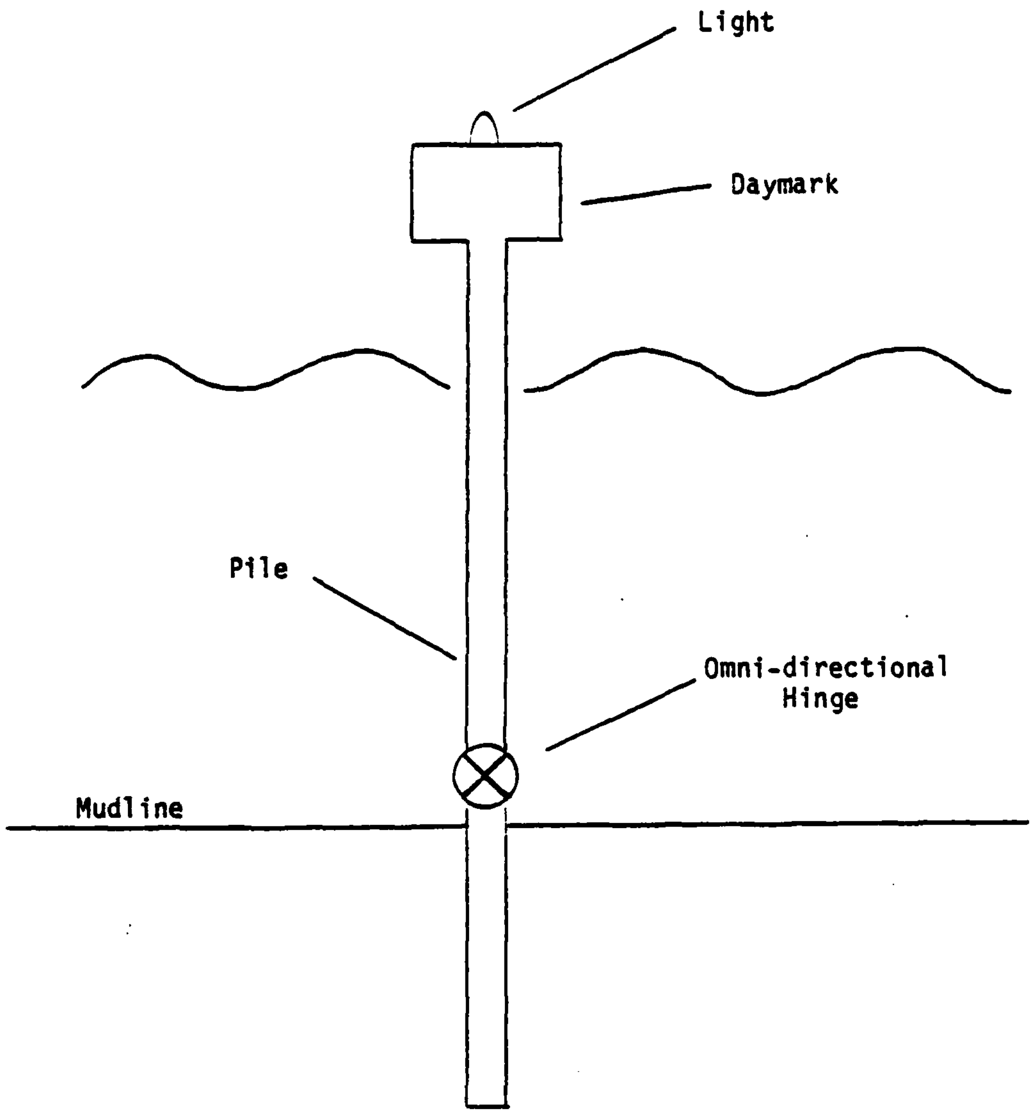


Fig. 1. Schematic of CTPS system. Major components include the navigation aid, a rigid pile section and a flexible hinge held in position by a base pile driven into the sediment.

capability of being installed by existing Coast Guard construction vessels which can routinely drive piling but do not have crews capable of sophisticated welding or metal work. Logistical design requirements are given in Table 1. Operational requirements include maintaining a position within an "envelope" of near-vertical inclination angles when acted upon by weight and environmental loads such as wind, wave and current forces. Design verticality limits, weight and environmental loadings are specified in Table 2. As a design goal, the structure should also survive (without daymark) the hurricane conditions given in Table 3. Lastly the Coast Guard requests that the CTPS be able to withstand the barge collision outlined in Table 4.

The CTPS design life must be 5 years. The design goal for cost is under $5,000, while the maximum cost, based on 10 units/year, must not exceed $10,000.

DESIGN APPROACH

Determining the feasibility of meeting the design requirements and developing the best design solution for the hinge component were accomplished using computer simulations and laboratory testing of a physical scale model. Major elements of the design and analysis program include computer modeling of the pile dynamics, hinge component development, construction of a physical scale model, testing of the model's verticality performance in a water channel and observing the model's collision response during experiments conducted in a pool.

The initial task was to develop computer programs to predict pile performance under the various conditions referred to in the design requirements. Assumptions and key equations in the mathematical development are outlined in Section II. The computer simulations were used to relate the overall design criteria to hinge stiffness characteristics thus providing a basis for hinge component development. The computer models were also used as an aid in interpreting experimental data and to predict the performance of a full-scale prototype.

Table 1. Logistical requirements

(a) Installation, maintenance and removal of the structure must be accomplished by existing Coast Guard construction vessels and must not require the use of divers or sophisticated underwater equipment.

(b) Proposed structure must not impose serious departures from present practices of pile fabrication and installation and must fit within the capabilities of existing vessels.

(c) Any single component of the structure must not exceed 50 feet by 20 inches in size or weight more than 10,000 lbs.

(d) When removed for repair or replacement the designed structure must be retrieved intact or constructed to separate at or below the mudline in order not to become a hazard to navigation.

Table 2. Verticality, weight load and environmental requirements. The structure must support the dead load plus live load and two daymarks. The structure must meet the verticality requirement with dead load and daymarks under the environmental conditions.

Verticality	$\pm$ 5° (design goal)	$\pm$ 10° (maximum allowable)
Dead Load	350 lbs	
Live Load	200 lbs	
Daymarks	2 at 36 ft^2 each located 7 ft above MHW	

Environmental conditions	Design goal	Minimum allowable
Water Depth Maximum	30 ft.	20 ft.
Minimum	10 ft.	15 ft.
Current	3 kts.	2 kts.
Wind	60 kts (gusts) 50 kts (sustained)	60 kts (gusts) 40 kts (sustained)
Waves - Height	5 ft.	4 ft.
Period	3-5 sec.	3-4 sec.
Bottom Slope	15°	15°
Bottom Consistency	Soft Clay	Soft Clay

Table 3. Hurricane conditions. As a design goal the structure should survive and return to normal operation after the following hurricane conditions with dead load less daymark.

Hurricane Conditions	Quantitative Extent
Water Depth Maximum	30 ft. (design goal), 20 ft. (allowable)
Minimum	10 ft. (design goal), 15 ft. (allowable)
Storm Surge	9 ft.
Current	3 kts. (design goal), 2 kts. (allowable)
Wind	100 kts. (gusts, 75 kts. (sustained)
Waves - Height	6 ft.
Period	4-6 sec.
Bottom Slope	15°
Bottom Consistency	Soft Clay

Table 4. Barge Collisions. The structure must survive the following collision conditions and return to normal operation.

Collision Condition	Quantitative Extent
Barge speed	10 kts. (maximum)
Bottom clearance between mudline and barge	3 ft. (minimum)
Number of collisions	5 per year (maximum)

Using guidelines established by the computer modeling effort, a hinge concept was chosen and developed as discussed in Section III. The selected design and construction details for scale model fabrication are presented in Section IV. Next the actual hinge stiffness characteristics were measured in out-of-water experiments (referred to in this report as "bench" tests). Results for hinge moment as a function of angle are given in Section V.

The water channel, verticality tests conducted at the Coast Guard Academy and collision tests carried out at the UNH indoor pool are discussed in Sections VI and VII, respectively. These experimental results were then used to refine parameters selected for the final set of computer simulations, described in Section VIII, which predict full-scale behavior of the selected design. Logistical and cost factors are presented in Section IX. Conclusions drawn from this study are summarized and recommendations for prototype development are made in Section X.

II. PILE DYNAMICS MODELING

MODELING APPROACH

Computer programs were developed for modeling the dynamics of pile systems under conditions referred to in the design criteria. Since the overall CTPS design criteria given in Tables 2-4 refer to distinct and very different conditions, several computer models were developed. Programs were written for operating conditions in which small angle verticality restrictions must be met, hurricane conditions in which forcing and angular motion may be larger, and collision conditions in which barge contact is the dominant feature. All models, however, share some common assumptions and, as a consequence, many dynamic equations are the same for all applications. General features of the modeling approach are discussed here, while the specifics of individual computer programs are detailed in the following subsections. Program listings are given in Appendix A.

The CTPS is considered to be a flexible hinge-rigid beam-mass system such as that shown in Fig. 2. The hinge is omnidirectional and possesses restoring moment stiffness. Weight and current forcing are external loads common to all major computer models, while wind, wave and barge contact forcing may or may not be present depending on the application. In all models, the directions of current and (when present) wind, wave and barge motion are assumed collinear corresponding to the worst case situation.

The governing dynamic equation for the hinge-beam-mass system considered is the time rate of change of angular momentum equation applied at the (fixed point) hinge,

$$I_H \ddot{\theta} = \Sigma \text{ M's} \qquad (1)$$

where I_H = moment of inertia about the hinge, θ = angle of pile with respect to the vertical, ($\ddot{\ }$) indicates two derivatives of ( ) with respect to time t, and M refers to moments applied about the hinge. (All terminology used is summarized in the NOMENCLATURE section).

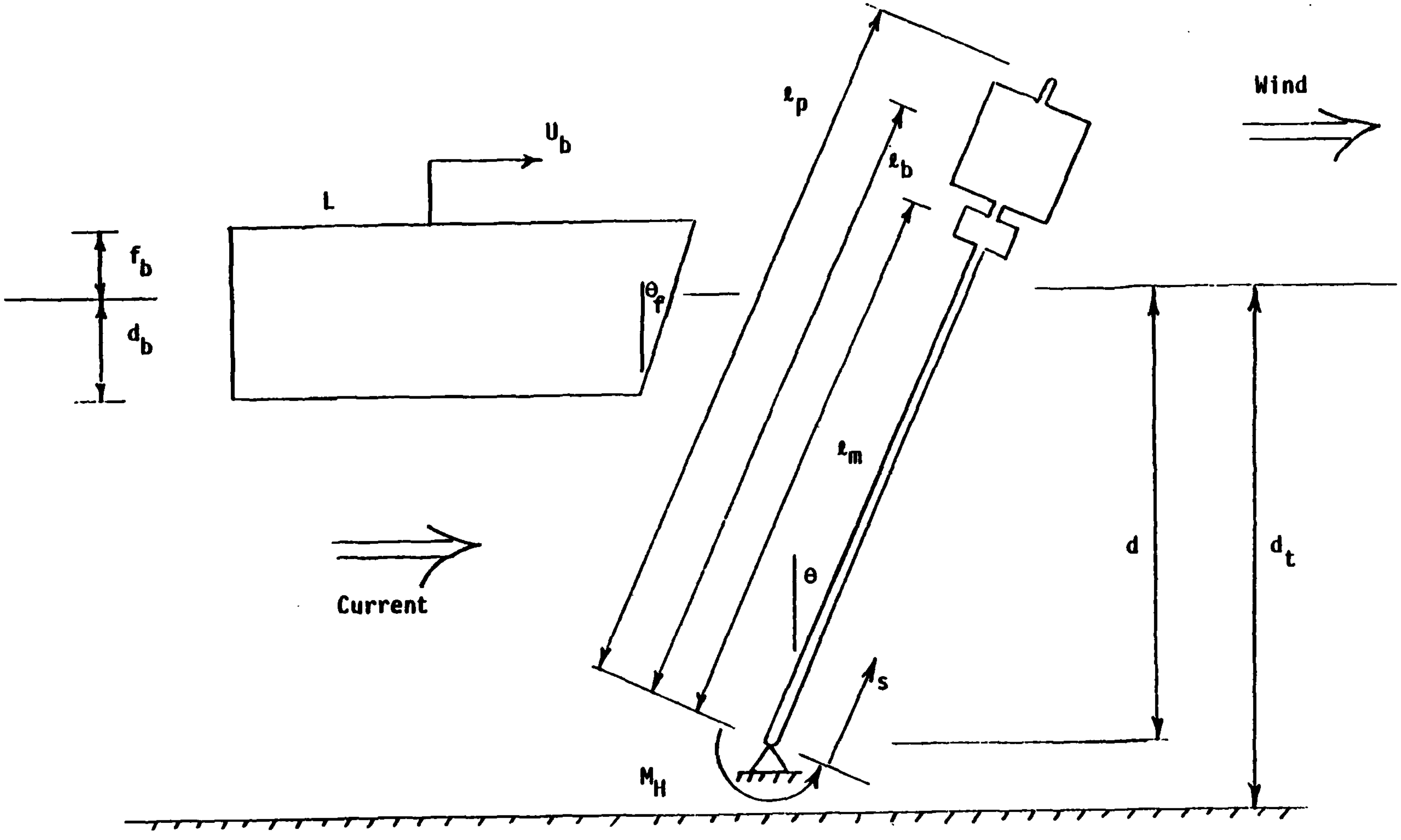


Fig. 2. CTPS nomenclature. The CTPS consists of a flexible hinge, a rigid beam pile, a mass near the top representing the load, and the daymark boards. Barge and environmental parameters are also indicated.

The flexible hinge will be constructed to provide a restoring moment to the CTPS. It is desired to have the hinge be very stiff at small angles to meet the verticality requirement under operating conditions. Yet hinge moment stiffness at the large angles encountered during collisions should be limited in order to reduce maximum pile bending moment. The piece-wise linear behavior of hinge moment $M_H = M_H(\theta)$ shown in Fig. 3 has these characteristics and is used in the models. The hinge's behavior at small angles is determined by the initial stiffness (slope) k_1, while properties at large angles are additionally influenced by the large angle stiffness (slope) k_2. It is desirable to have $k_1 \gg k_2$, and the breakpoint angle (point of slope change) should be at the limit of the CTPS's operating range.

The upsetting gravitational moment, M_G, due to pile and load weight has the mathematical form

$$M_G = \ell_m \sin\theta \, W_\ell + 1/2 \, \ell_p \sin\theta \, W_p \tag{2}$$

where lengths ℓ_m and ℓ_p are shown in Fig. 2 and W_ℓ and W_p are load and pile weights, respectively. Hollow piles are assumed free-flooding, and the restoring moment effect due to bouyancy is neglected.

The moment load induced by relative water movement, M_C, is evaluated using a form of Morrison's equation,

$$M_C = \int_0^{\ell_s} s[\frac{1}{2} \; \rho_w \, C_w \, d_p u_r^2 + C_m(\frac{\pi d_p^2}{4}) \, \rho_w \, \dot{u}_r] \, ds \tag{3}$$

where s = pile coordinate shown in Fig. 2, ℓ_s = submerged length, ρ_w = water density, C_w = drag coefficient of the pile in water, C_m = inertia coefficient of the pile, d_p = pile diameter, and u_r = relative velocity normal to the pile. The relative velocity includes steady current, motion of the pile itself and wave fluid velocity. Wave motion is taken as that of a regular (single frequency), small amplitude (linear) surface wave. Thus the wave fluid velocity components are

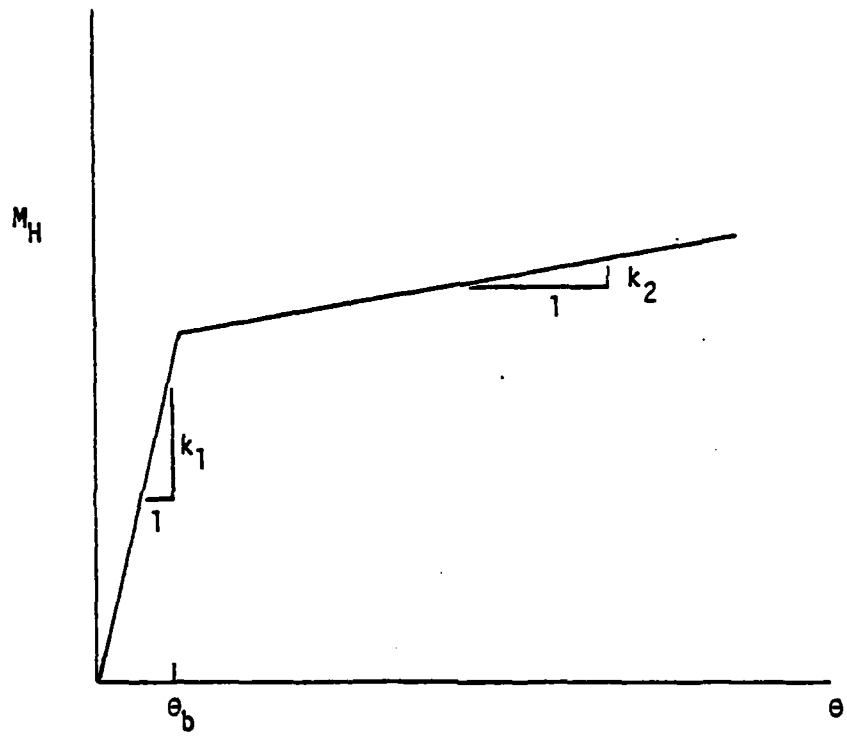


Fig. 3. Piece-wise linear hinge moment behavior. The initial stiffness k_1 is the slope at small angles; k_2 is the slope at large angles. The break point angle is θ_b.

$$u_w = \frac{\sigma H_w}{2} \left(\frac{\cosh k(d_t+y)}{\sinh kd_t}\right) \cos(kx-\sigma t)$$

and

$$v_w = \frac{\sigma H_w}{2} \left(\frac{\sinh k(d_t+y)}{\sinh kd_t}\right) \sin(kx-\sigma t) \tag{4}$$

where σ = wave radian frequency, H_w = wave height, $k = 2\pi/\lambda$, λ= wavelength, d_t = water depth and x,y are horizontal, vertical coordinates with their origin at the mean water level directly above the hinge.

The overturning moment acting on the pile as a result of (steady) wind, M_W, is evaluated using a drag coefficient approach. An approximate expression for wind moment can therefore be written in the form:

$$M_W = 1/4(\ell_p^2 \cos^2\theta - d^2)\, \rho_a\, C_a\, d_p U_a^2 + 1/2\, \ell_b \cos\theta\, \rho_a\, C_b\, A_b\, U_a^2 \tag{5}$$

in which distances d and ℓ_b are shown in Fig. 2, ρ_a = air density, C_a = drag coefficient of the pile in air, C_b = drag coefficient of daymark boards, A_b = area of boards, and U_a = wind velocity. The first term on the right hand side (RHS) is set to zero should the pile become entirely submerged, and the second is zero when the boards are sacrificed.

During a collision, the barge contact force contributes a moment about the hinge, M_B, which is of the form

$$M_B = F_B\, \ell_c \sin\theta_c \tag{6}$$

where F_B = barge contact force, ℓ_c = distance from hinge to point of contact and θ_c = angle between pile direction and direction of barge force.

The general pile dynamic expressions given by Eqs. 1-6 serve as the basis for modeling the specific conditions stated in the design criteria. Equation specialization, solution approaches and computer programs based on the mathematical theory are discussed in the following subsections for each application.

PRELIMINARY ANALYSIS

Two computer models were developed to assist in the initial determination of CTPS design parameters and to provide a preliminary assessment of the system's static and dynamic characteristics. The computer program PILESTIFF calculates the initial hinge moment stiffness k_1 (see Fig. 3) necessary to meet a specified verticality requirement under static equilibrium conditions. The program PILEFREQ computes a specified pile system's undamped natural frequency.

PILESTIFF is helpful in the early stages of design when a trial value for k_1 is needed. This can be obtained by ignoring the oscillations induced by waves and solving the corresponding static equilibrium problem. Under static conditions the left hand side (LHS) of Eq. 1 is zero, while the RHS includes moment contributions given by Fig. 3 and Eqs. 2,3 and 5 (no barge contact). The wave fluid velocity contribution, given by Eqs. 4 to the relative velocity (u_r) in Eq. 3 is, however, zero. For small angles, the resulting moment equilibrium equation is easily rearranged to provide the following formula for k_1:

$$k_1 = \ell_m W_\ell + \frac{1}{2}\ell_p W_p + [\frac{1}{4}(\ell_p{}^2 - d^2)\rho_a C_a d_p U_a{}^2 + \frac{1}{2}\ell_b \rho_a C_b A_b U_a{}^2 + \frac{1}{4}d^2 \rho_w C_w d_p U_c{}^2]/\theta. \tag{7}$$

The user of PILESTIFF specifies the static angle desired, all other CTPS design parameters, and the wind, current and weight loading. PILESTIFF then uses Eq. 7 to compute the value for k_1.

PILEFREQ calculates the CTPS undamped natural frequency which is useful in identifying potential resonant situations from wave loading or other sources of periodic forcing. The angular momentum equation is used in which wave excitation and fluid damping (Eq. 3), wind forcing (Eq. 5), and barge contact (Eq. 6) are neglected from the RHS. The remaining hinge moment (Fig. 3) and weight moment (Eq. 2) terms are linearized yielding the harmonic oscillator equation from which the natural frequency ω_0 is easily identified as

$$\omega_o = [(k_1 - \ell_m W_\ell - \frac{1}{2}\ell_p W_p)/I_{HT}]^{1/2} \tag{8}$$

where $I_{HT} = \frac{1}{3}m_p\ell_p^{\ 2} + \ell_m^{\ 2}\ m_\ell + \frac{\pi}{12}\rho_w C_m d_p^{\ 2} d^3$, m_p = mass of pile and m_ℓ = mass of load.

PILEFREQ computes natural frequency (and period) using Eq. 8 and CTPS design parameters supplied by the user.

OPERATING CONDITIONS

The computer program OPPILE was developed to model pile dynamics during operating conditions. The principal use of this model is to determine whether the CTPS designs under consideration meet the verticality requirement specified in Table 2. Thus the program predicts inclination angle and hinge moment response for specified pile dimensions, hinge stiffness and load conditions.

The model is based on the angular momentum equation, Eq. 1, with piecewise linear hinge stiffness behavior (see Fig. 3) and loads due to weight, current, wave, pile motion relative to the fluid, and wind as provided by Eqs. 2,3 and 5. Since the operating restrictions require that the pile be nearly vertical, small angle approximations are used and the boards are assumed not to submerge.

Coupling with lateral motion is neglected. The possibility of transverse excitation by vortex shedding was investigated, and motion due to this source was found negligible for full scale CTPS's meeting the design criteria. Reynolds numbers ($\sim 6\times10^5$) exceed the critical Reynolds number so that the wake is fully turbulent with little coherent vortex street structure as discussed by Weigel (1964) and others. Lift coefficients (C_L) in this range, as reported for example by Sarpkaya (1976) and Schewe (1982), drop to the range $.03 < C_L < .20$. In addition the natural frequency of pile oscillation was found to be much slower than the shedding frequency, so the system's dynamic response is very small.

The specialized dynamic equations are solved using a Runge-Kutta numerical technique. At each time step, the along-pile integrations required by Eq. 3 are completed using the trapezoidal rule. No stability problems were encountered,

and accurate results were obtained for time steps less than a tenth of the wave period.

The program user must supply pile and hinge design parameters, wind and current velocities, water depth, and wave height, period and length. A utility program, WAVELENGTH, was written to assist the user in specifying consistent wave parameters. Specifically the program calculates wavelength for user specified depth and wave period by solving the following transcendental equation from small amplitude wave theory:

$$\lambda = \frac{gT^2}{2\pi} \tanh\,(2\pi d_t/\lambda) \tag{9}$$

where λ = wavelength, g = gravitational acceleration and T = wave period. Wavelength λ is computed using the Newton-Raphson iteration method.

When input to OPPILE is complete, the program calculates and prints out time series for inclination angle θ and hinge moment M_H. Steady state response is generally achieved within 3 wave periods.

HURRICANE CONDITIONS

The computer program HURPILE was developed to model pile dynamics during hurricane conditions such as those described in Table 3 of the design criteria. HURPILE is actually very similar to OPPILE. The main difference is that HURPILE is not limited to small inclination angles. The pile may be entirely submerged and rotate up to θ = 90 deg without loss of accuracy. The large angle capability, however, necessitates approximately three times the computer time. Another important characteristic is that the boards are assumed to have been sacrificed. From the user's point of view, input and output format are virtually identical to that of OPPILE.

COLLISION CONDITIONS

The computer programs COLPILE and RECPILE were developed to model pile dynamics during collision conditions. COLPILE was used to predict angular position, barge loads and hinge reactions during a head-on (worst case) barge collision. RECPILE predicts pile motion and hinge moment as the pile recovers to an upright position after the CTPS has been overrun. A discussion of COLPILE appears immediately below and is subsequently followed by a description of RECPILE.

The complete collision, as modeled by COLPILE, consists of a sequence of processes. Initially there is impact of the top of the barge bow with the pile, then sliding of the pile occurs along the top of the bow and the bow face. Next there is impact of the bottom of the bow rake with the pile followed by sliding along this point. Lastly, the tip of the pile slides along the barge bottom before being released. The program analyzes these processes in chronological order.

The major assumption throughout the collision analysis is that because the barge is so massive, it's motion is essentially unaffected by the collision. Barge speed therefore remains constant. In addition, it is assumed that the boards are sacrificed, and wind and wave forces are considered negligible in comparison with collision forces.

The constant barge speed condition enables the pile kinematics to be analyzed independently of the forces involved. Since the horizontal velocity component of the pile contact point must equal the barge speed, θ, $\dot{\theta}$ and $\ddot{\theta}$ may be determined as function of time from the problem geometry.

Next, CTPS dynamics are analyzed using the rate of change of angular momentum equation, Eq. 1, in which the moment sum includes the hinge moment M_H, the gravitational moment M_G, the fluid force moment due to current and relative pile motion (no waves) M_C, and the barge moment M_B. Using the kinematic results, M_H, M_G and M_C are evaluated using Fig. 3, Eq. 2 and Eq. 3, respectively. Similarly the rate of change of angular momentum term, $I_H\ddot{\theta}$, in Eq. 1 is calculated from the barge kinematics. Eq. 1 is then used to compute barge moment M_B.

Note that unlike OPPILE and HURPILE, Eq. 1 is not "solved" in the usual sense of evaluating $\theta = \theta(t)$. The constant barge speed constraint and geometry determines angular position independently, and Eq. 1 is simply used to calculate the unknown barge moment, M_B, term.

Using the M_B result and collison geometry, Eq. 6 is applied to compute the barge contact force F_B. Having determined F_B, the linear momentum equations (Newton's Second Law) are applied vertically and horizontally to evaluate the hinge reaction forces R_V and R_H, respectively.

While the collision analysis described above is theoretically correct throughout the sequence of collision processes, it is convenient to modify the approach somewhat at the two instants of impact. At these times, the weaker non-impulsive loads due to fluid motion and the hinge moment are neglected, and COLPILE uses the impulse-momentum form of the reduced equations of motion. Eq. 1, for example, becomes

$$(I_H\dot{\theta})_{t_f} - (I_H\dot{\theta})_{t_i} = \Sigma\int_{t_i}^{t_i} M\, dt \qquad (10)$$

where t_i and t_f are initial and final times, respectively, bracketing the impact process and the RHS includes only impulsive moments. The same steps previously outlined are taken yielding results for barge moment impulses and barge and hinge reaction force impulses.

The program user must supply COLPILE with CTPS design parameters, barge dimensions and speed, current velocity and water depth. The user also specifies the interval between times for which output is desired. Results consist of angle, hinge moment, barge moment (or moment impulse), barge force (or force impulse), and reaction forces (or force impulses).

The program RECPILE is used to model pile recovery after being released from beneath the barge bottom. Initial position is specified by the user (from COLPILE results), then RECPILE calculates angular motion and hinge moment as the pile returns to the upright position. RECPILE is actually a modification of

HURPILE thus making use of HURPILE's large angle capability. Changes include omitting wind and wave excitation and allowing the user to specify the initial conditions for θ.

The user of RECPILE must input the CTPS design parameters, current and water depth as well as the initial inclination angle. The program responds by calculating and printing out time series for θ and M_H.

III. HINGE COMPONENT DEVELOPMENT

INITIAL CONCEPT DEVELOPMENT

At first, the very simple and inexpensive rubber tube hinge suggested by Miller (1982) was considered. In this concept, flexibility is achieved by using a section of rubber tube as shown in Fig. 4. Piecewise linear behavior is obtained by having the wall thickness thin enough so that the compressive side buckles at large angles.

The moment as a function of angle relationship for the rubber section at small angles can be determined from beam theory. This approach can therefore be used to estimate the initial stiffness k_1. For small angles,

$$\frac{M_H}{\theta} = k_1 = \frac{EI}{\ell_r} \tag{11}$$
$$= (E/\ell_r)[\pi/4(r_o^4 - r_i^4)],$$

where E = Young's modulus, I = area moment of inertia for the rubber tube cross-section, and ℓ_r, r_o and r_i are the tube dimensions shown on Fig. 4.

If the pile consists of a 12 inch wooden pole, the computer models indicate that a k_1 value of at least 3.5×10^5 ft-lbs/rad is necessary to meet the operating inclination limit of the design criteria. Using $r_i = 6$ in, $r_o = 9$ in, $\ell_r = 18$ in (commensurate with a relatively thick-walled section) and E = 1200 psi (which is an extremely stiff example), k_1 is estimated to be 2.3×10^4 ft-lbs/rad. Since this result is less than an order of magnitude smaller than the necessary value, the rubber hinge concept was not developed further.

It became clear that achieving sufficient initial stiffness would be a major obstacle. To address this problem, other concepts involving a very large, central spring were considered as discussed by Swift and Baldwin (1984). The central spring would be housed within the pile itself. Thus the next phase of modeling activity focused on the analysis of systems using 18 inch steel pipe for the pile section.

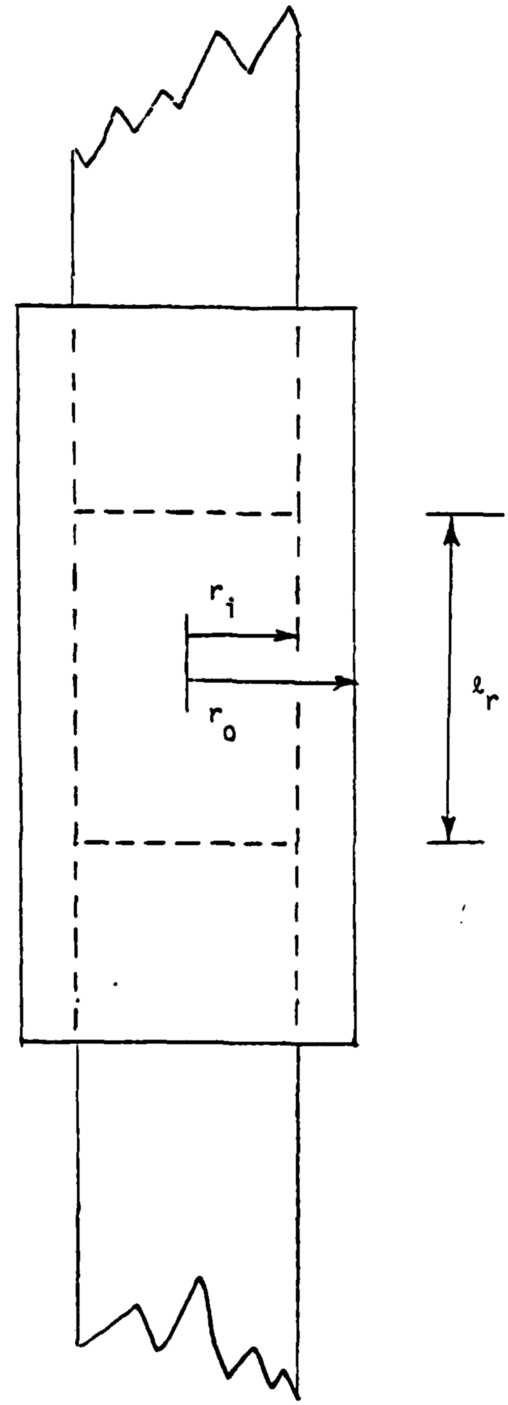


Fig. 4. The rubber tube hinge concept.

PRELIMINARY MODELING

The computer models were applied to a trial case, "Design CTPS" in order to establish guidelines for further hinge component selection and development. A summary of the tests and conclusions is presented here, while details are included in the interim report by Swift and Baldwin (1984). The "Design CTPS" consisted of an 18 inch, Schedule 20 steel pipe pile with lengths chosen for the maximum operating water depth of 30 ft. Wind velocity, current velocity and wave heights were set at maximum values, and pile performance was computed for all design conditions and some typical situations not explicitly addressed by the design criteria.

An initial stiffness, k_1, value of approximately 6×10^5 ft-lbs/rad (or, equivalently, 10^5 ft-lbs at 10 deg) was found necessary to meet the maximum inclination limit, under worst case operating conditions, of 10 deg. This k_1 value results in a 5 deg angle under the corresponding static environment, that is, the same maximum current and wind but no waves. The optimum breakpoint angle was found to be 10 deg as this provides the largest stiffness during operating conditions and immediate stiffness reduction beyond the operating range. A large angle stiffness, k_2, of approximately 1/10 k_1 resulted in prompt pile recovery after collision and could be reduced further. Since a minimum moment of approximately 10^5 ft-lbs is necessary to initiate recovery at 90 deg, k_2 should not normally be negative.

Impact of the barge with the pile at the bottom of the bow rake was found to be very sensitive to bottom clearance. When hinge clearance was less than approximately 7 ft, force impulses on the pile and reaction forces supporting the hinge base became excessive. Thus the mudline clearance of 3 ft specified in Table 4 could result in impact forces causing local damage at points of contact and possible loosening of the base. Typical barges using channels in the Houston area, on the other hand, have drafts of less than 12 ft. For this more common situation, collision loads were determined to be tolerable.

FINAL CONCEPT DEVELOPMENT

The preliminary computer analysis had shown that the hinge component must meet certain performance requirements in order for the entire CTPS to meet the overall design specifications. For the CTPS to meet the minimum verticality requirement, the initial stiffness constant, k_1, should be approximately $6x10^5$ ft-lbs/rad, and the breakpoint angle is best at 10 deg. The large angle stiffness is less critical and may be roughly between zero and 1/10 k_1. Lastly, the hinge must be able to rotate down from the vertical a full 90 deg for all horizontal angles, and the attachment must be able to sustain large impact loads.

Several hinge concepts were considered, and their potential performance characteristics were compared with these hinge criteria. (Examples of hinge component designs considered but not adopted, besides the rubber tube hinge, are reviewed in Appendix B). The system found to be best able to meet the hinge criteria is the central universal joint, prestressed peripheral stay concept illustrated in the Fig. 5 schematic. The two axes of the universal joint are off-set vertically to prevent binding at any point in the range of articulation. Four stays are attached to the base, led upwards over spreaders and into the (hollow) pile, and connected to a central spring. The spring is prestressed so that all stays are equally taut when the pile is vertical. The arrangement is such that if there is an angular change from the vertical, the stay on the outside of the bend immediately takes up the entire prestress force. Thus a large restoring moment is generated at very small angles.

The prestress moment is essentially r_sF_s where r_s = radius of stay location and F_s is the prestress force. Ideally this is imposed for the smallest deviation from the vertical. Because the real system is non-ideal (due to friction and compliance of the components), some finite angle change must occur before M_H increases to r_sF_s. To be sure that the necessary initial stiffness is achieved, the prestress moment is set at the computer model hinge moment evaluated at the

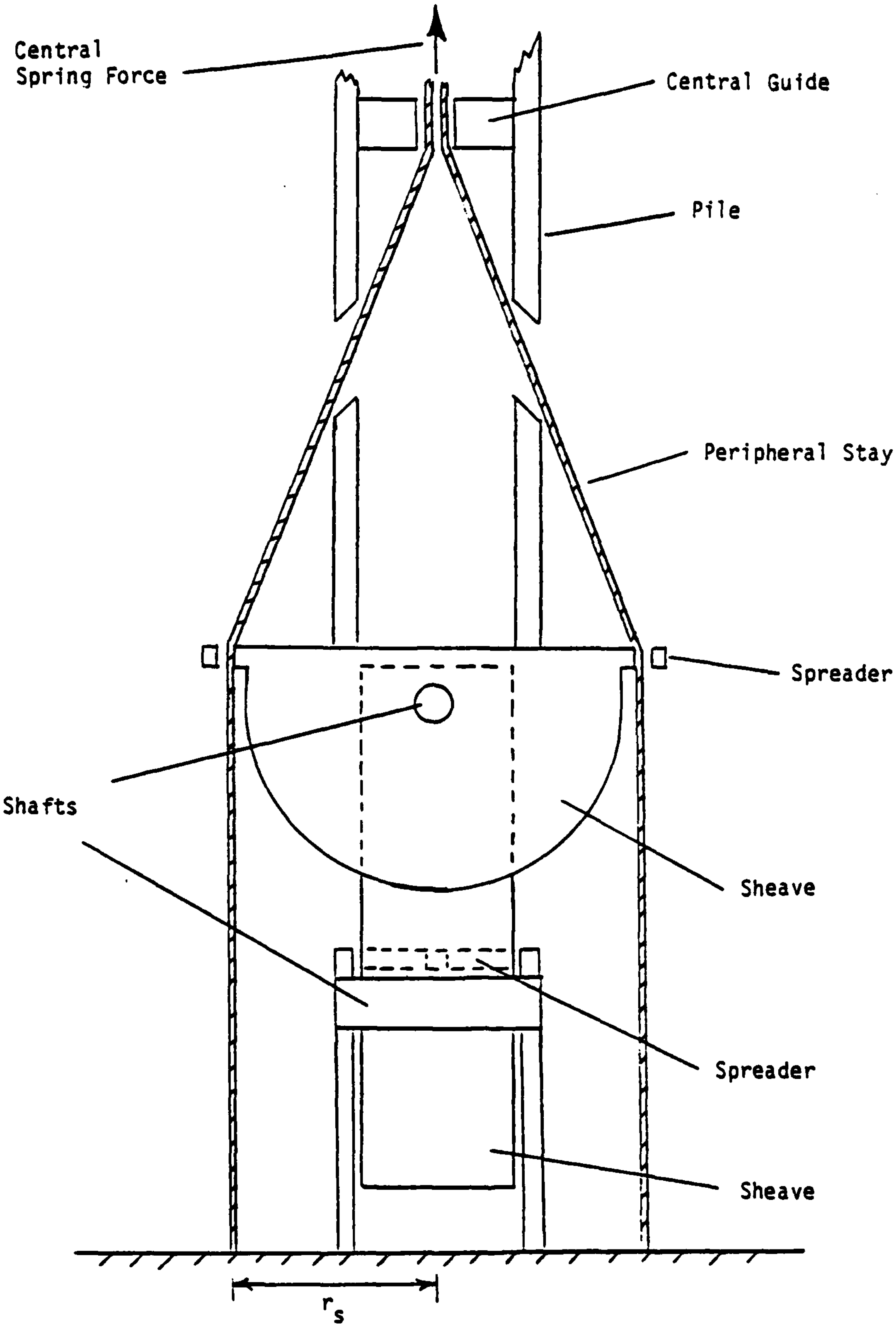


Fig. 5. Schematic of the central universal joint, prestressed peripheral stay concept.

limit of the operating range (that is, 10 deg). The prestress force is therefore designed to be

$$
\begin{aligned}
F_s &= 1/r_s \; (M_H(\theta = 10°)) \\
&= 1/r_s \; k_1 \; (10\pi/180) \qquad (12)
\end{aligned}
$$

Half-circular sheaves are attached below in order to maintain stay moment arm with respect to the hinge axis. With the arm distance fixed, the hinge moment normally increases slowly at large angles as the prestressed spring is extended further.

The "spring" used must have the capacity for providing the prestress force given by Eq. 12 and have the elastic range necessary for hinge angles up to 90 deg. The "spring" must also fit inside the pile. Possible options include rubber bands, an array of nylon ropes or a piston/cylinder (air bag sealed) concept. Further discussion of "spring" options is included in Appendix C.

IV. CTPS DESIGN AND MODEL CONSTRUCTION

PILE SYSTEM DESIGN

The central universal joint/peripheral stay hinge concept was incorporated into the pile system design shown in Fig. 6. CTPS parameters were selected so that the system would be operable in 30 ft. of water as specified in the design criteria. The pile supports two angled 6 ft by 6 ft daymark boards (face view of one shown in Fig. 6) and a load consisting of a light/battery pack. These are located 7 ft above the high water level as recommended in the Coast Guard aid-to-navigation manual.

The pile itself consists of an 18 inch steel pipe and contains the spring (one of the options discussed previously). The spring is attached at the lower end to the stays just above a central stay guide. The upper end is secured to a worm gear arrangement for prestressing the system and adjusting individual stay tautness. Thus the stay controls are accessible from the top.

The hinge design follows the central universal joint/prestressed peripheral stay concept described in the previous section. The spring pretension force was evaluated using computer model results and Eq. 12. Our preliminary computer analysis indicated that if k_1 is determined using a 5 deg inclination angle criteria under static worst case operating conditions, the dynamic response should not exceed the 10 deg maximum angle when waves are present. PILESTIFF was, therefore, used to compute an initial stiffness k_1 = 577,770 ft-lbs/rad from which a spring prestress force F_s = 67,200 lbs was calculated using Eq. 12. Because the sheaves maintain stay moment arm at large inclination angles, k_2, though small, should not be negative. The hinge is secured to a heavy base connected to an embedded pile section.

Since this design was developed in accordance with the design guidelines established in the previous section, it was anticipated that the system would meet the design criteria. Further evidence was obtained by testing a physical scale model and conducting a complete series of computer simulations as described

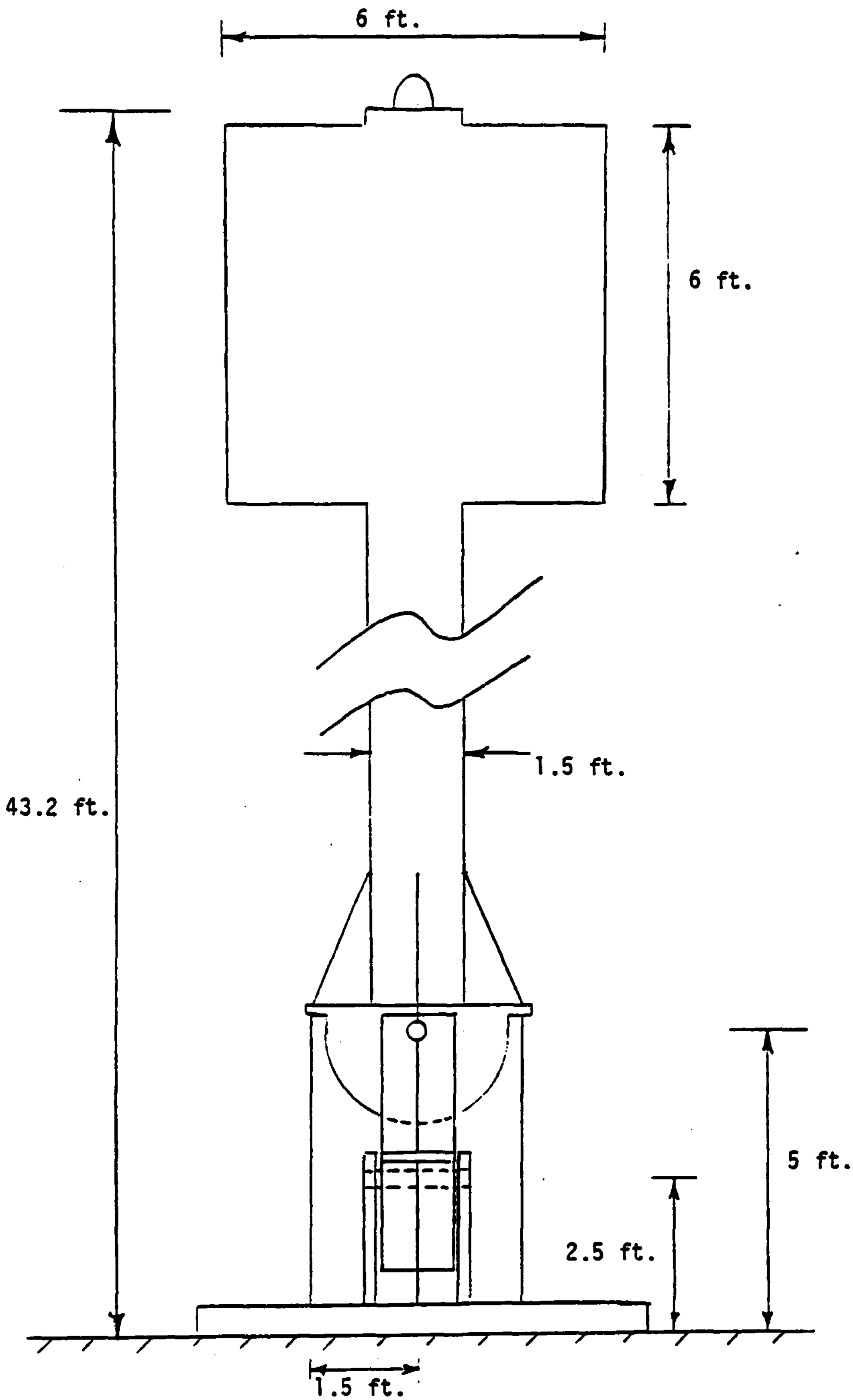


Fig. 6. The CTPS design for a maximum operating depth of 30 ft. System weight for all components above the lower shaft is 4634 lbs. Weight for the 18 in pile only is 2890 lbs , and "load" weight (including all hardware as well as the beacon) is 1744 lbs and is located 8.84 ft above the lower shaft. For all components above the upper shaft, total weight is 3740 lbs , pile weight is 2716 lbs , "load" weight is 1024 lbs and is located 12.07 ft above the upper shaft.

in following sections. Scaling considerations and construction details for the physical model are presented in the remainder of this section.

SCALING CONSIDERATIONS

Planning for the construction and testing of the physical model required that scaling decisions be made. The model would, of course, be built so that its shape is scaled geometrically and mass and weight are proportional to L_r^3 where $L_r = (\ell_p)_{Model}/(\ell_p)_{Full\ Sized}$. A more complete scaling system, however, needed to be devised in order to establish other parameters such as speeds and stay tensions.

In view of the fact that both inertial and gravitational forces play a crucial role in the pile dynamics, it was decided that Froude scaling would be adopted for the water channel and pool experiments. Holding Froude number ($= U/\sqrt{gd_p}$ = (inertial forces/gravitational forces)$^{1/2}$) constant in a constant gravitational environment results in velocities and time scales proportional to $\sqrt{L_r}$. Consequently $I_H \ddot{\theta} \propto (\text{length})^2(\text{mass})(\text{time})^{-2} \propto L_r^4$; from Eq. 2, $M_G \propto L_r^4$, and from Eq. 3, $M_C \propto L_r^4$, .

In order that the dynamic scaling of Eq. 1 be consistent, it is also required that $M_H \propto L_r^4$ and therefore $F_s \propto L_r^3$. It should be noted that this represents a reduction at the model size from that obtained by straight geometric scaling. Since in general, $F_s \propto$ (elastic constant)(strain)(cross-section area), using the same material and geometrically imposing the same initial strain causes $F_s \propto L_r^2$. *Thus if spring material is unchanged, F_s must be further reduced* to comply with $F_s \propto L_r^3$ scaling. This may be achieved by reductions in initial strain, cross-section area or both.

The system of scaling outlined here was used as the basis for specifying parameters for the physical scale model fabrication described in the next subsection.

The scaling method was also employed in all physical model experiments as discussed in the following sections.

MODEL CONSTRUCTION

A physical scale model was constructed to correspond to the full scale design shown in Fig. 6. A scale ratio $L_r = 1/15$ was chosen so that the specified high water operating condition (depth = 30 ft) could be tested at model scale in the Coast Guard water channel (depth = 2 ft). Construction drawings of the model are provided in Figs. 7-10, and a photograph of the hinge assembly is shown in Fig. 11.

In order to minimize complicated fabrication tasks, make use of standard sections and to provide sufficient local strength, major components of the model are overly thick. Consequently material substitutions were necessary to maintain correctly scaled weights. The pile itself is made of PVC pipe rather than steel, and aluminum is substituted for steel in the hinge assembly.

A very simple, conveniently available rubber band is used as the "spring." This is pre-stressed to a force of 19.9 lbs ($= L_r^3 (F_s)_{\text{Full Scale}} = (1/15)^3\ 67{,}200$) corresponding to a k_1 value of 11.4 ft-lb/rad ($= L_r^4 (k_1)_{\text{Full Scale}} = (1/15)^4\ 577{,}700$). A reel for prestressing the rubber band is positioned at the top. Since stay moment arm with respect to the hinge axis is maintained by the sheaves at large angles and spring tension increases slightly with angle, k_2 is expected to be small but positive. Its exact value, however, will depend greatly on internal friction and is difficult to quantify theoretically.

Fine adjustment of stay tension is provided in the model by use of turnbuckles located at the base. Each stay is led through a base attachment eye then to a turnbuckle which lies horizontally just above the base. This system enables convenient tuning for model experiments. The full-scale design, of course, will have all tension gear accessible from the top as noted previously.

Flexible wire rope was chosen for the stays because of its strength and availability at an appropriately small diameter. Kevlar is recommended for the

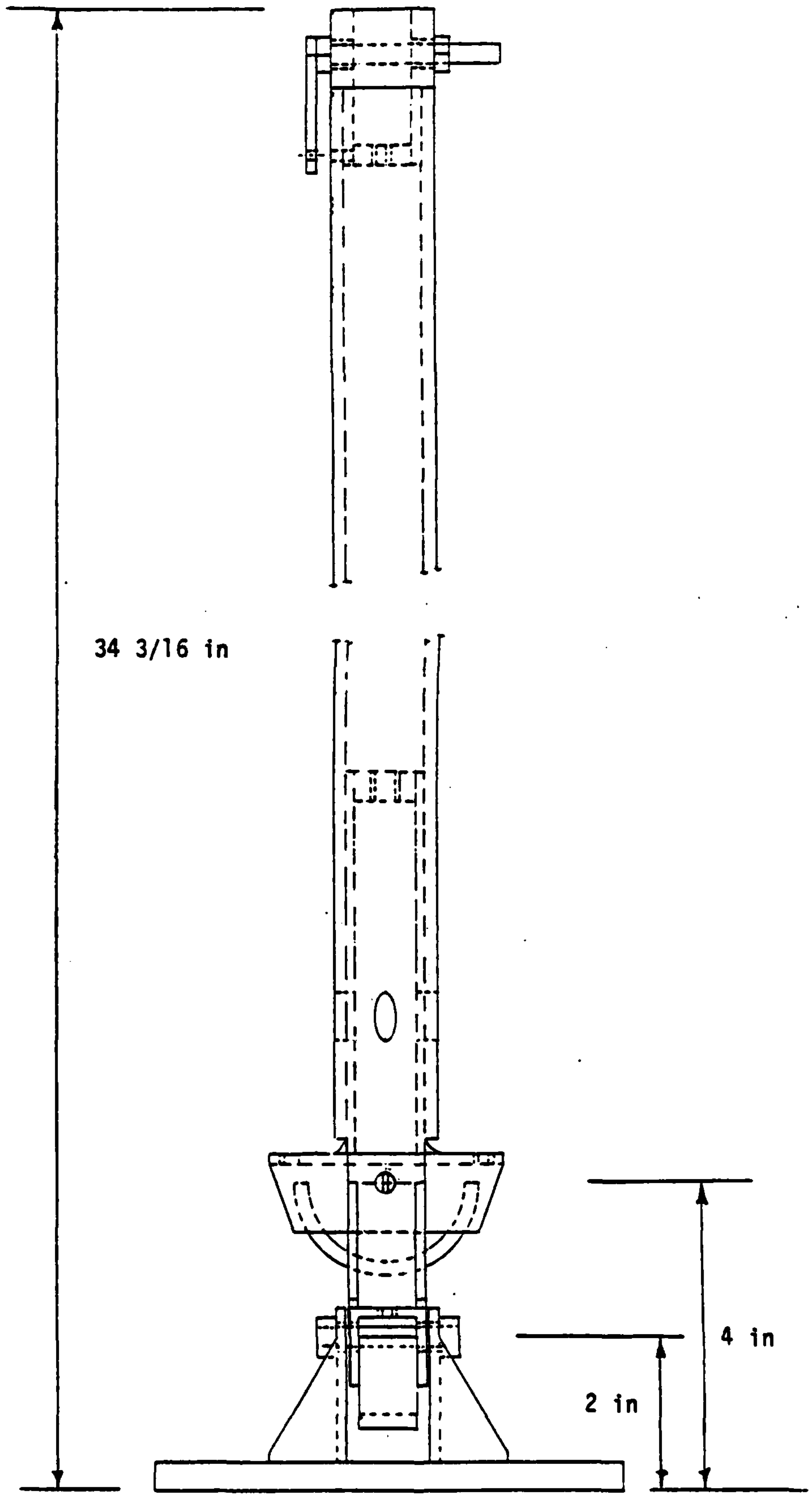


Fig. 7. The construction plan for the physical scale model. The central spring and the stays have been omitted for clarity.

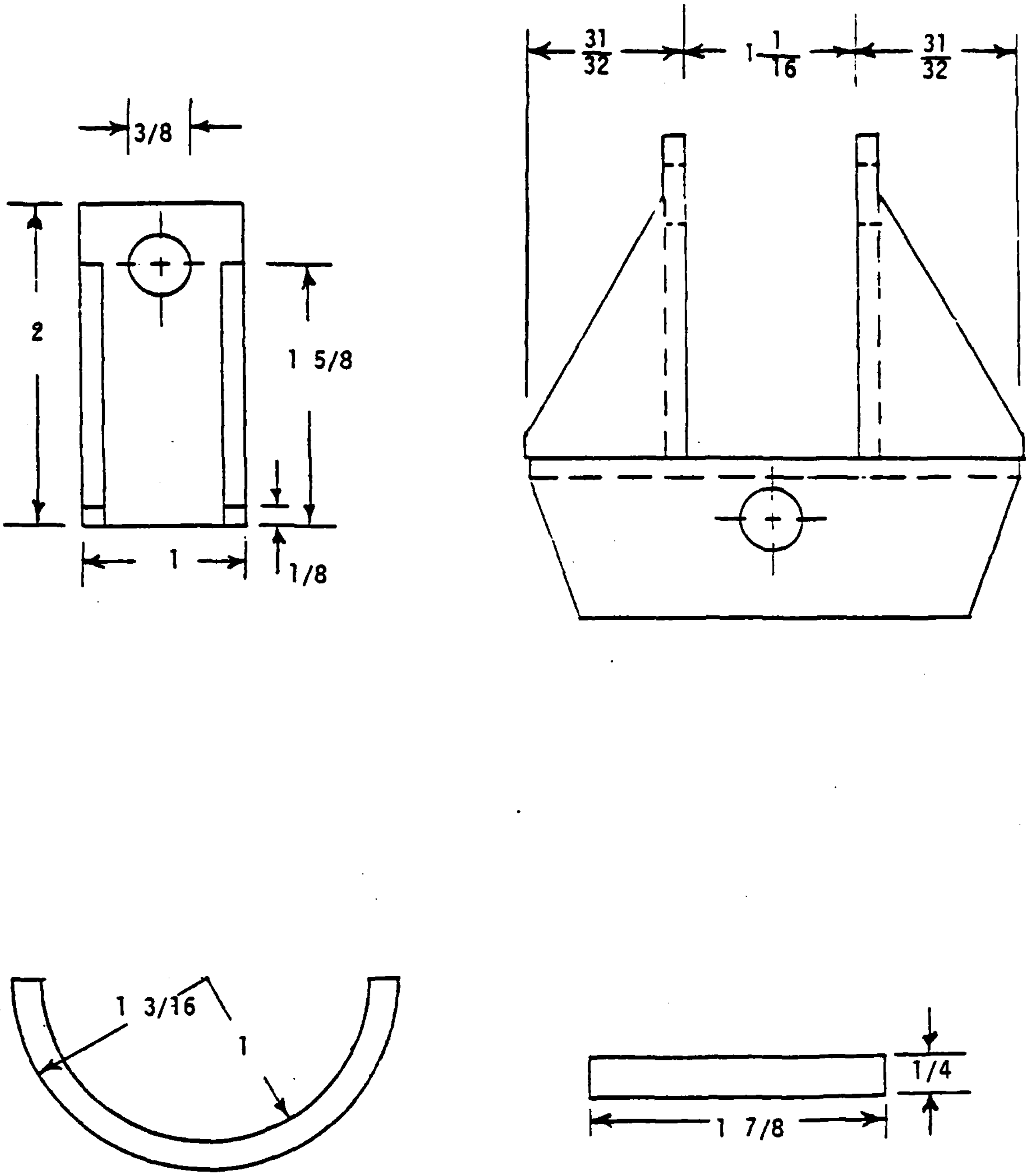


Fig. 8. Hinge component parts used in the lower shaft assembly.
Drawings are full scale, and dimensions are in inches.

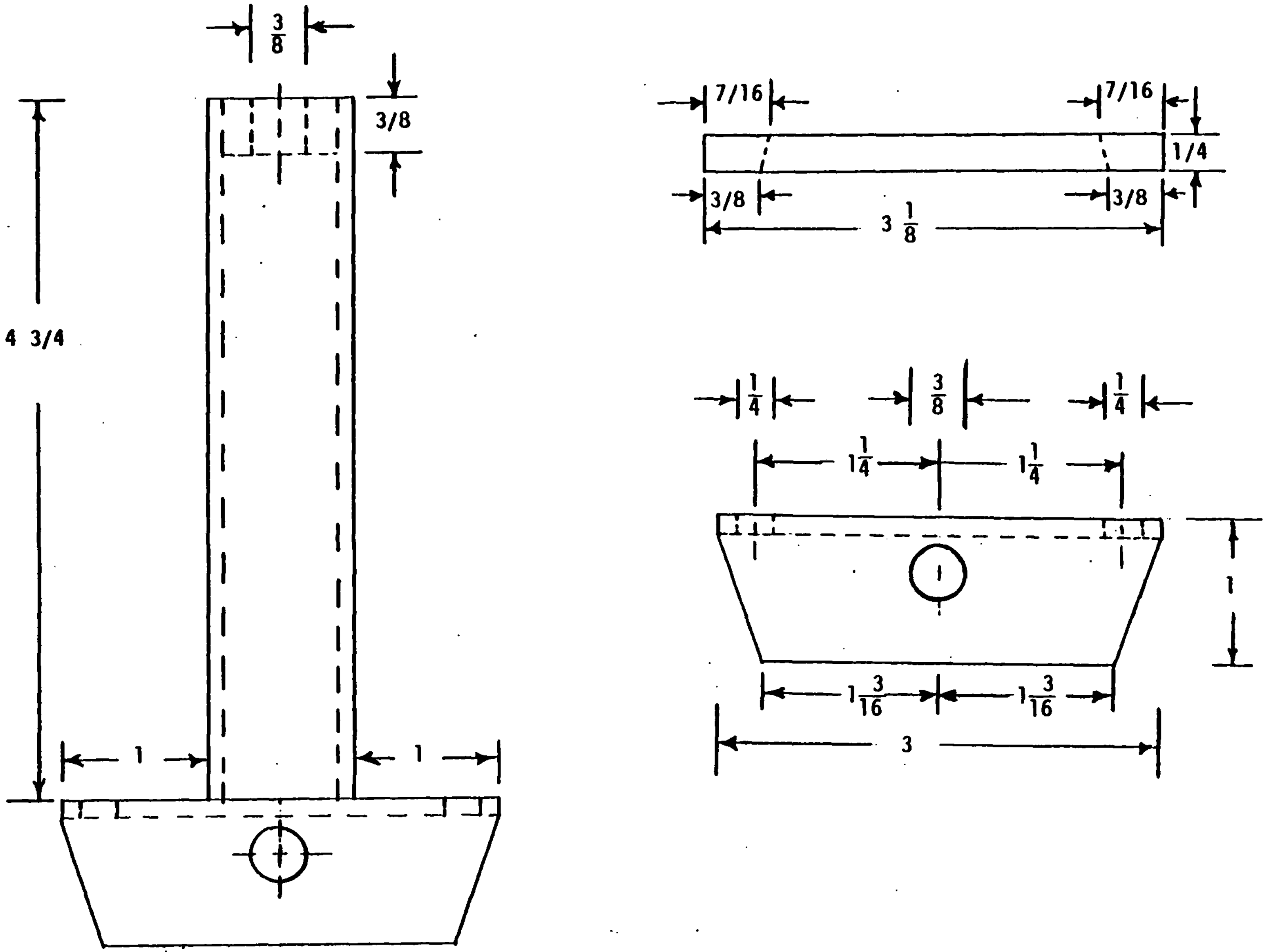


Fig. 9. Hinge component parts used in the upper shaft assembly
Drawings are full scale, and dimensions are in inches.

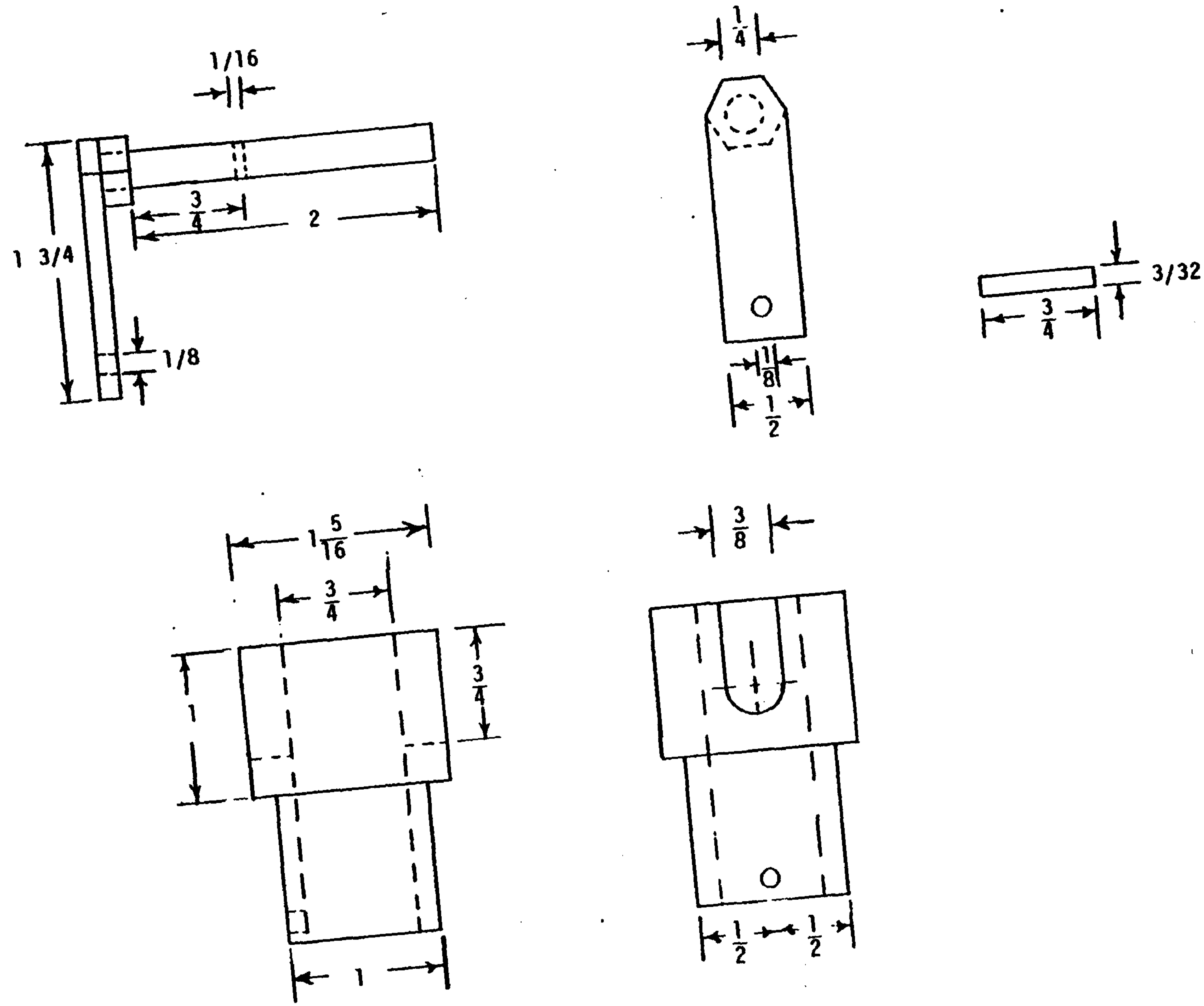


Fig. 10. Hinge component parts used in the spring prestressing assembly. Drawings are full scale, and dimensions are in inches.

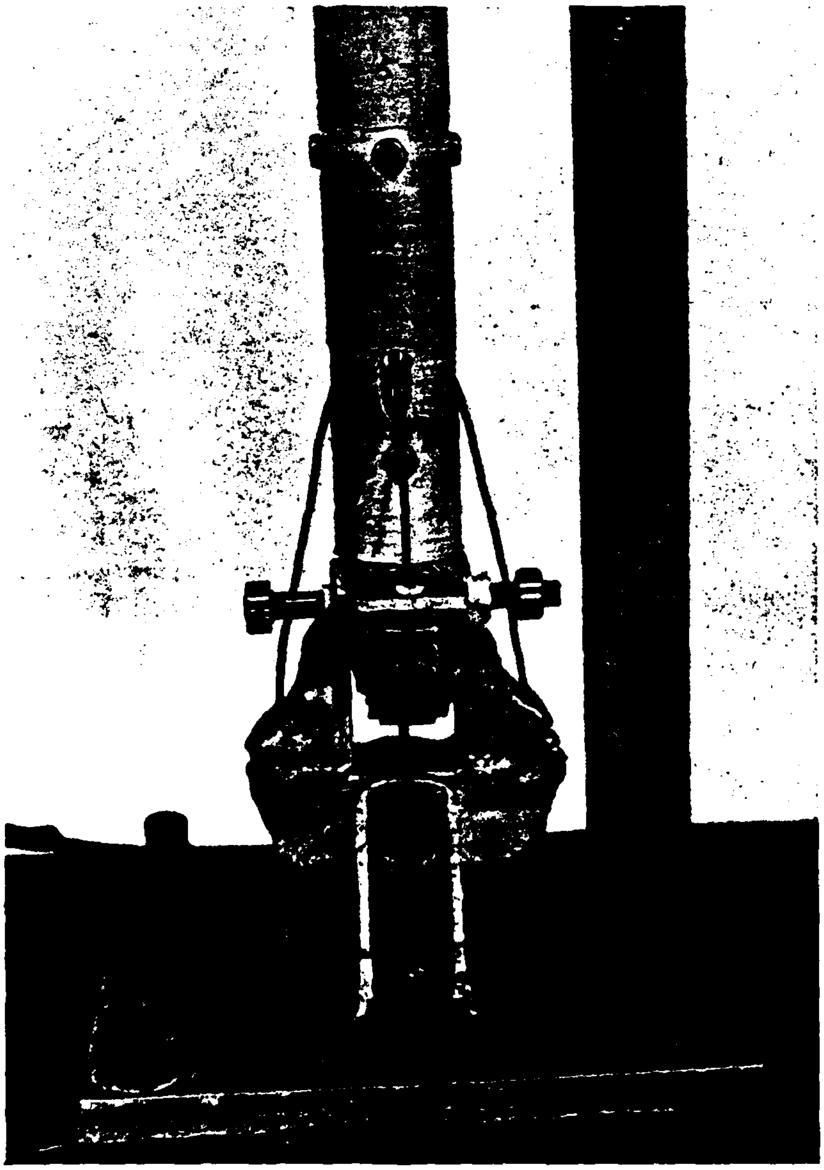


Fig. 11. Physical model hinge assembly. A vertical scale is provided which has units of inches.

full-scale prototype for corrosion resistance and minimum friction. In the model the additional friction associated with steel stays rubbing steel surfaces was reduced by use of teflon guide bushings wherever possible. Excessive stay friction in the model could not, however, be eliminated entirely.

V. HINGE MOMENT/ANGLE EXPERIMENTS

OBJECTIVE

With the properly scaled pile model built the next step was to obtain data to determine the actual hinge moment (M_H) vs. angle (θ) relationship. The testing produced plots of M_H vs. θ which defines the hinge behavior. Values of k_1 and k_2 were evaluated and compared with those obtained from the theoretical and design work.

INSTRUMENTATION AND PROCEDURES

Prior to the actual measurement of the M_H vs. θ relationship the spring was prestressed to the design value of F_s = 19.9 lbs. The actual main spring element incorporated in the model was pulled in an Instron testing machine to generate an axial force/elongation plot. To obtain the desired preload in the model, the spring element was elongated to the value corresponding to F_s = 19.9 lbs.

With the spring preloaded, a sequence of angular displacement, perpendicular force and moment arm measurements were recorded. This data was subsequently reduced to provide M_H vs. θ plots and values of k_1 and k_2.

The actual procedure and equipment employed in the measurements are shown schematically in Fig. 12. The pile was secured to a rigid table. An angle chart was oriented such that the vertex of the angle chart was in line with the axis about which the measurement was to occur. A pointer was attached to the pile to serve as an angle indicator. The force was applied at some distance above the axis of rotation by means of a block and line arrangement as shown in Fig. 12. The load cell in the line was used to measure the force. Adjustments were made in the line-block system to insure that the force was being applied perpendicular to the pile at each angle θ where data was recorded. The load cell was an Interface super mini load cell with a range from 0 to 10 lbs tension

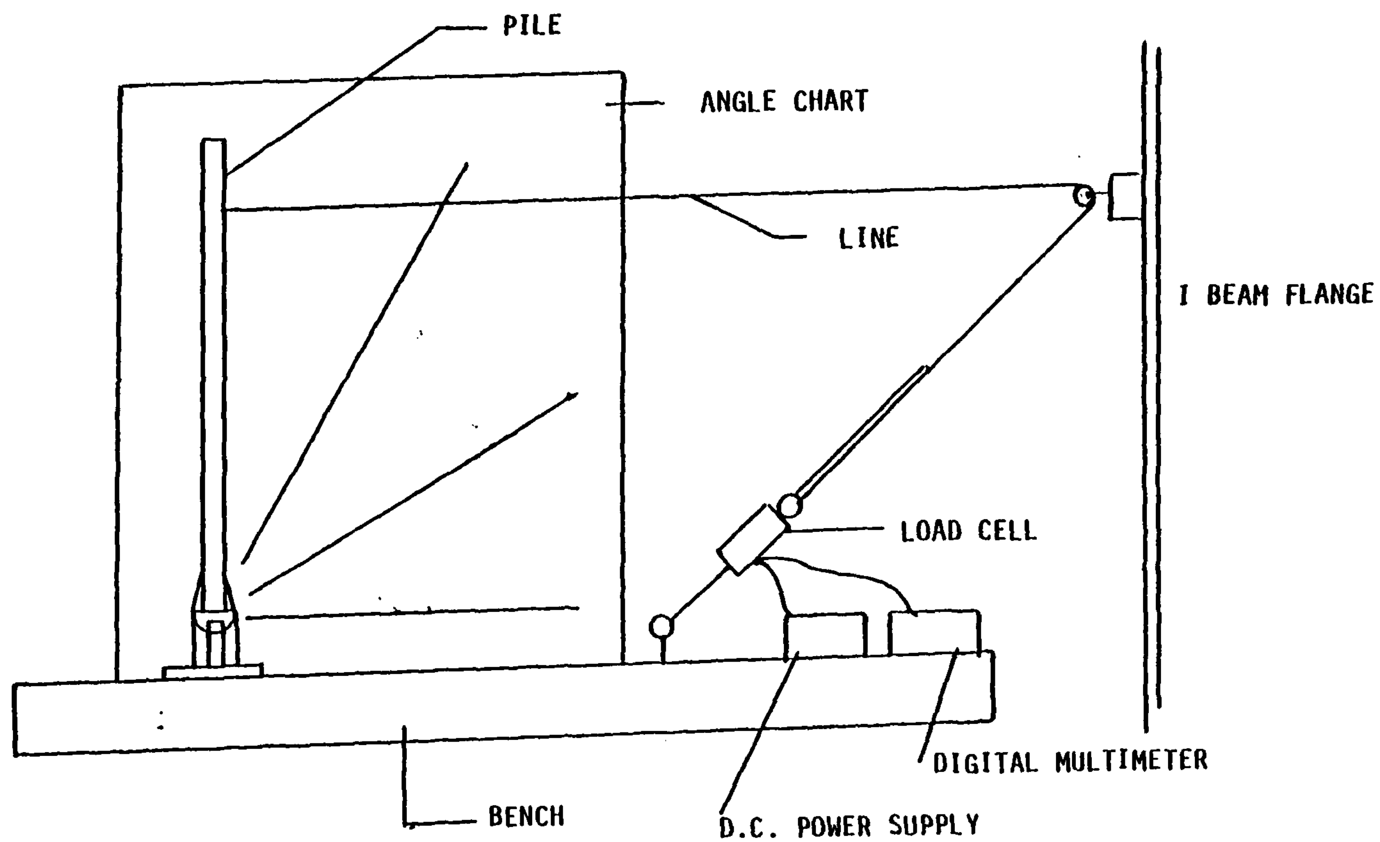


Fig. 12. Schematic for static bench test to determine the moment-angle relationship.

or compression. It was powered with a 5 volt dc power supply and the output was indicated on a Fluke digital multimeter. Data was obtained at 2° increments until 10° and then at 15° increments until the geometric limits of the measurement system were achieved, typically 60°.

Three pieces of information were obtained to provide one point on the M_H vs. θ plots - angle, moment arm and force. The moment arm times the force provided the measurement M_m. This value had to be corrected for the gravitational moment M_G given in Eq. 2. The gravitational moment was most significant at large values of θ. The correction was made using the following equation

$$M_H = M_m + M_G. \tag{13}$$

RESULTS

This procedure was employed for three cases: 1) rotation about the lower axis, 2) rotation about the upper axis and 3) an oblique case. In the oblique case the pile is displaced about both axes simultaneously. The data obtained for each case was reduced and plots of M_H vs. θ for each of the cases are shown in Figs. 13,14 and 15. The actual data points are indicated on each plot along with a least squares fit of a piecewise linear curve having a break at θ = 10 deg. Values of k_1 and k_2 were calculated from this least squares analysis and are provided on the plots.

The values of k_1 and k_2, summarized in Table 5, vary from case to case. The point to note is that the values of k_1 for the lower axis and oblique cases are within 10% of the design values. The values of k_1 for the upper axis case is higher and therefore conservative and acceptable. Though highly variable, all k_2 values correspond to hinge moments sufficient to return the pile to the vertical position from a horizontal starting point.

The difference between the upper and lower shafts was considered an artifact of the pretensioning fine tuning. The stays are adjusted in pairs to obtain

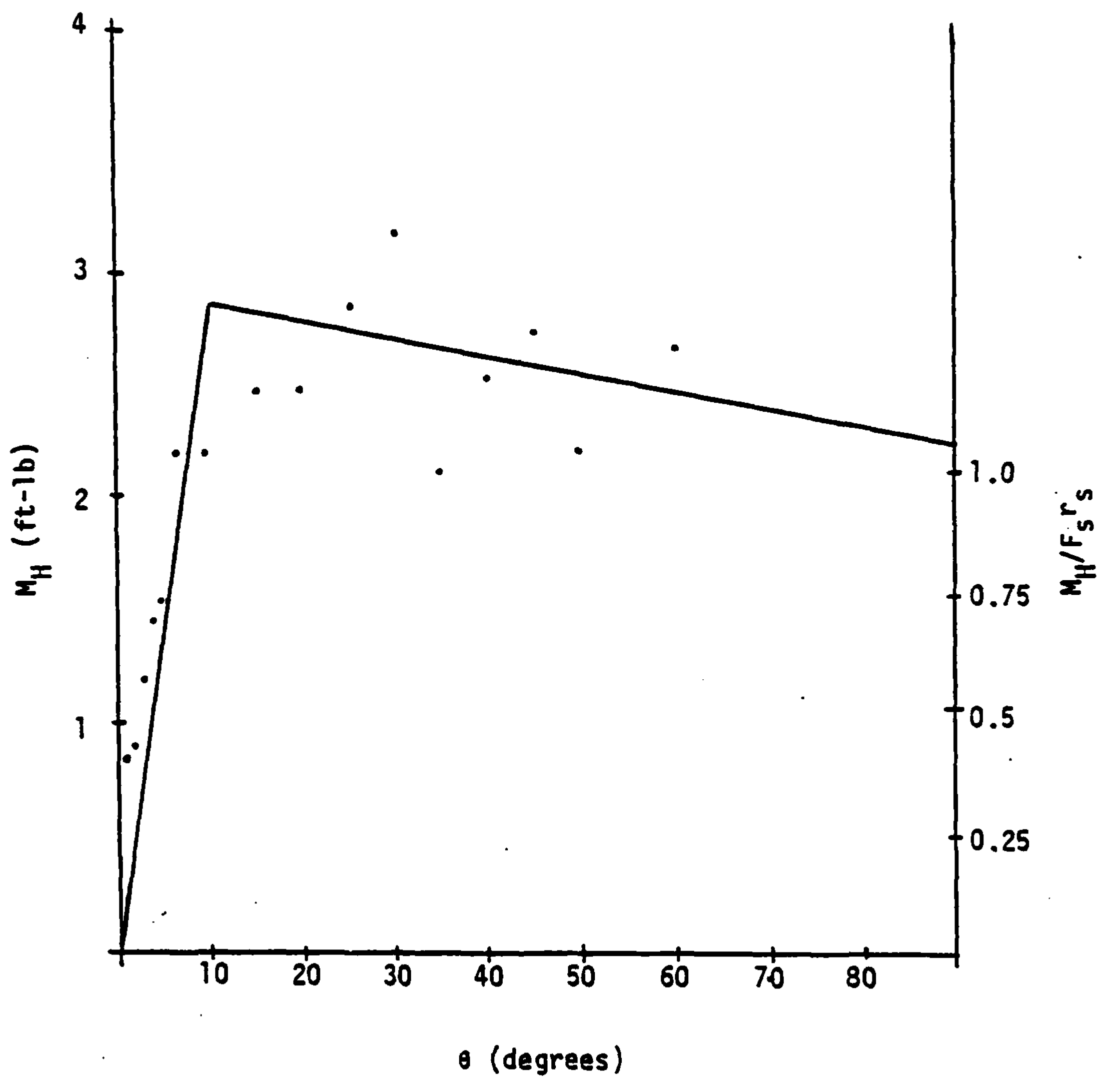


Fig. 13. Hinge moment about the upper axis vs. angle. A least squares fit of the data yields k_1 = 16.06 ft-lb/rad and k_2 = -.4352 ft-lb/rad (or k_1 = 0.2803 ft-lb/deg and k_2 = -0.0076 ft-lb/deg). The resulting piecewise linear curve is shown.

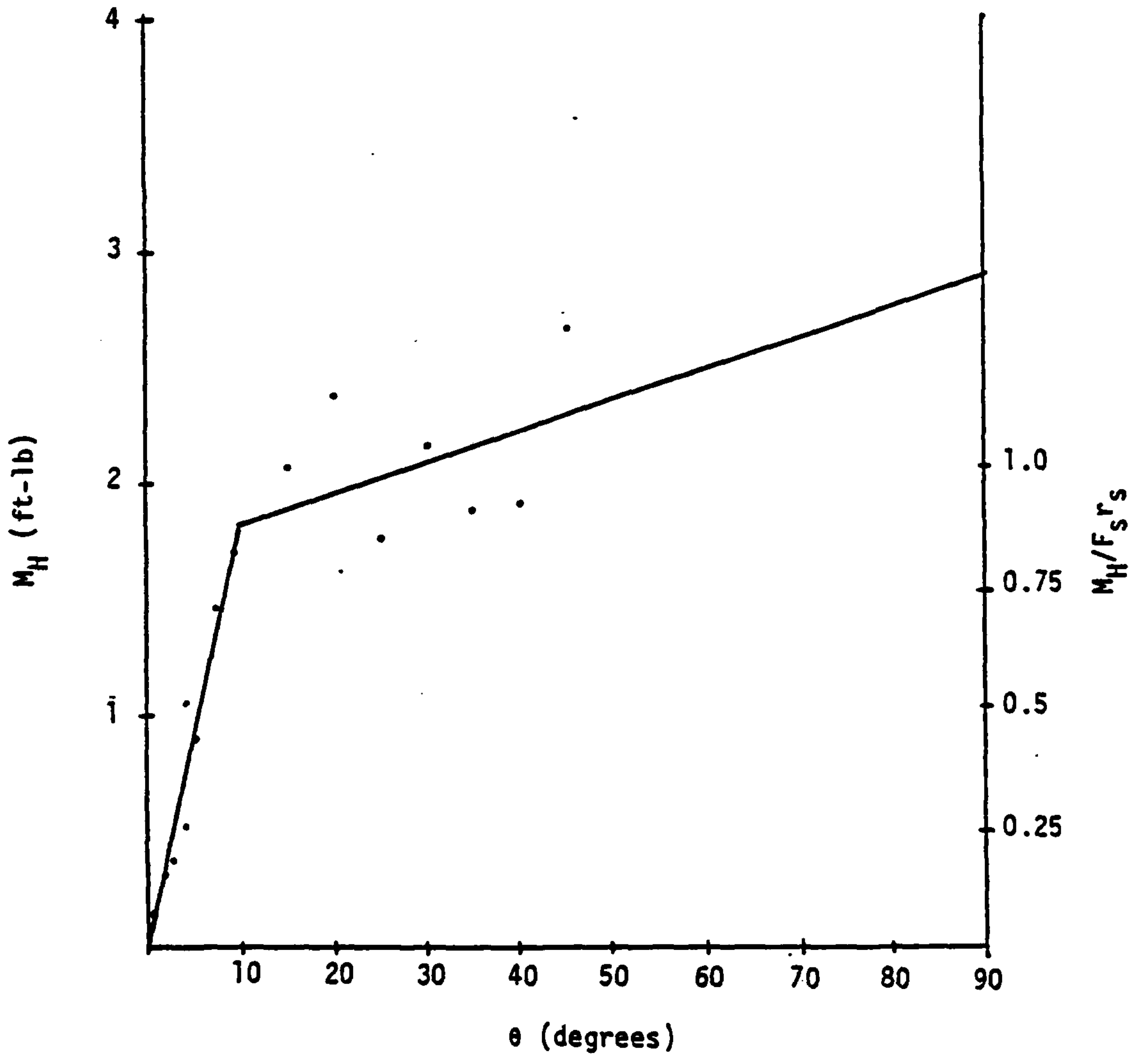


Fig. 14. Hinge moment about the lower axis vs. angle. A least squares fit of the data yields k_1 = 10.37 ft-lb/rad and k_2 = 0.0152 ft-lb/rad (or k_1 = 0.181 ft-lb/deg and k_2 = 0.0142 ft-lb/deg). The resulting piecewise linear curve is shown.

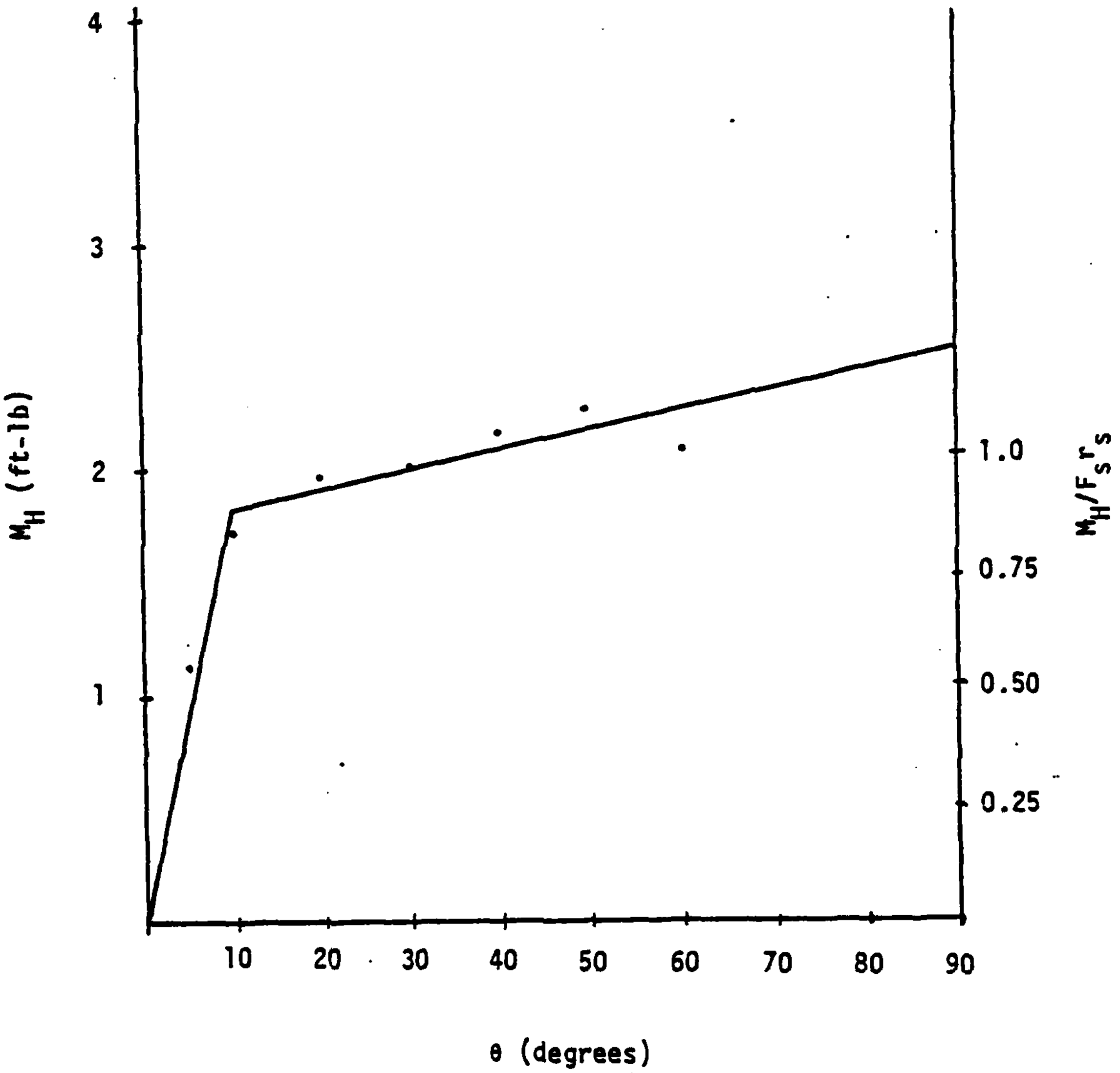


Fig. 15. Hinge moment oblique to the hinge axes vs. angle. A least squares fit of the data yields k_1 = 10.46 ft-lb/rad and k_2 = .5141 ft-lb/rad (or k_1 = 0.1825 ft-lb/deg and k_2 = 0.0084 ft-lb/deg). The resulting piecewise linear curve is shown.

Table 5. Summary of k_1 and k_2 values from the hinge moment vs angle experiments and a design value.

Case	k_1(ft-lb/rad)	k_2(ft-lb/rad)
Lower	10.37	.8152
Upper	16.06	-.4352
Oblique	10.46	.5141
Design	11.4	

verticality and consequently the resulting stiffness about each axis can vary. Internal friction and changes in spring properties may also play a role.

VI. WATER CHANNEL EXPERIMENTS

OBJECTIVES

The main objective was to determine if the model could satisfy the verticality requirement in a steady, uniform current. Secondary, yet important information regarding the hydrodynamic moment and drag coefficient was also an objective of these experiments. The uniform current testing was performed at the U.S. Coast Guard Academy Circulating Water Tunnel Facility (CWT) in New London, CT. Two types of experiments were performed to acquire the desired data. In the first experiment the pile inclination angle was measured as a function of the current speed. This allowed the observation and quantification of the verticality condition. In the second experiment the hydrodynamic moment was measured as a function of current speed. This relationship enabled the calculation of the drag coefficient.

INSTRUMENTATION AND PROCEDURES

In both experiments the pile base was secured to the bottom of the test section of the CWT. A bridge structure which straddled the test section was put in place and secured. This structure provided a fixed reference frame for measuring pile angle and attaching the load cell for moment measurements as shown in Figs. 16 and 17. The water speed (U_C) was varied from 0.6 ft/sec (2.3 ft/s full scale) to 1.4 ft/sec (5.4 ft/s full scale). The measured speed was determined by timing a wooden float in the flow over a 10 foot length a number of times and calculating an average speed.

Angle as a Function of Speed

The first experiment performed was the angle vs. water speed test. The spring was prestressed and fine tuned with the turnbuckles to achieve pile vertically, and the pile base was secured to the bottom of the test section. The horizontal

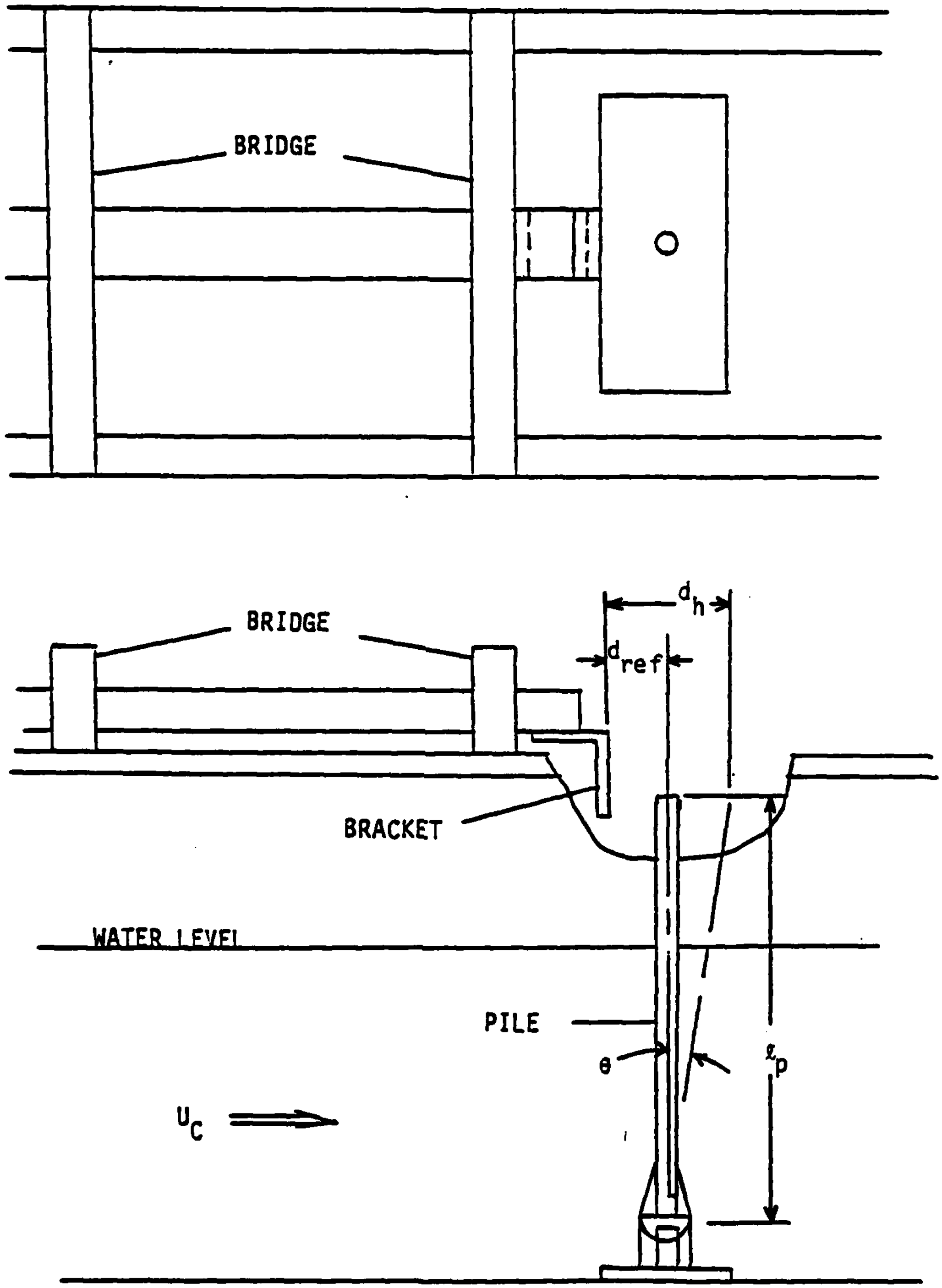


Fig. 16. Circulating Water Channel setup for angle vs. speed measurements.

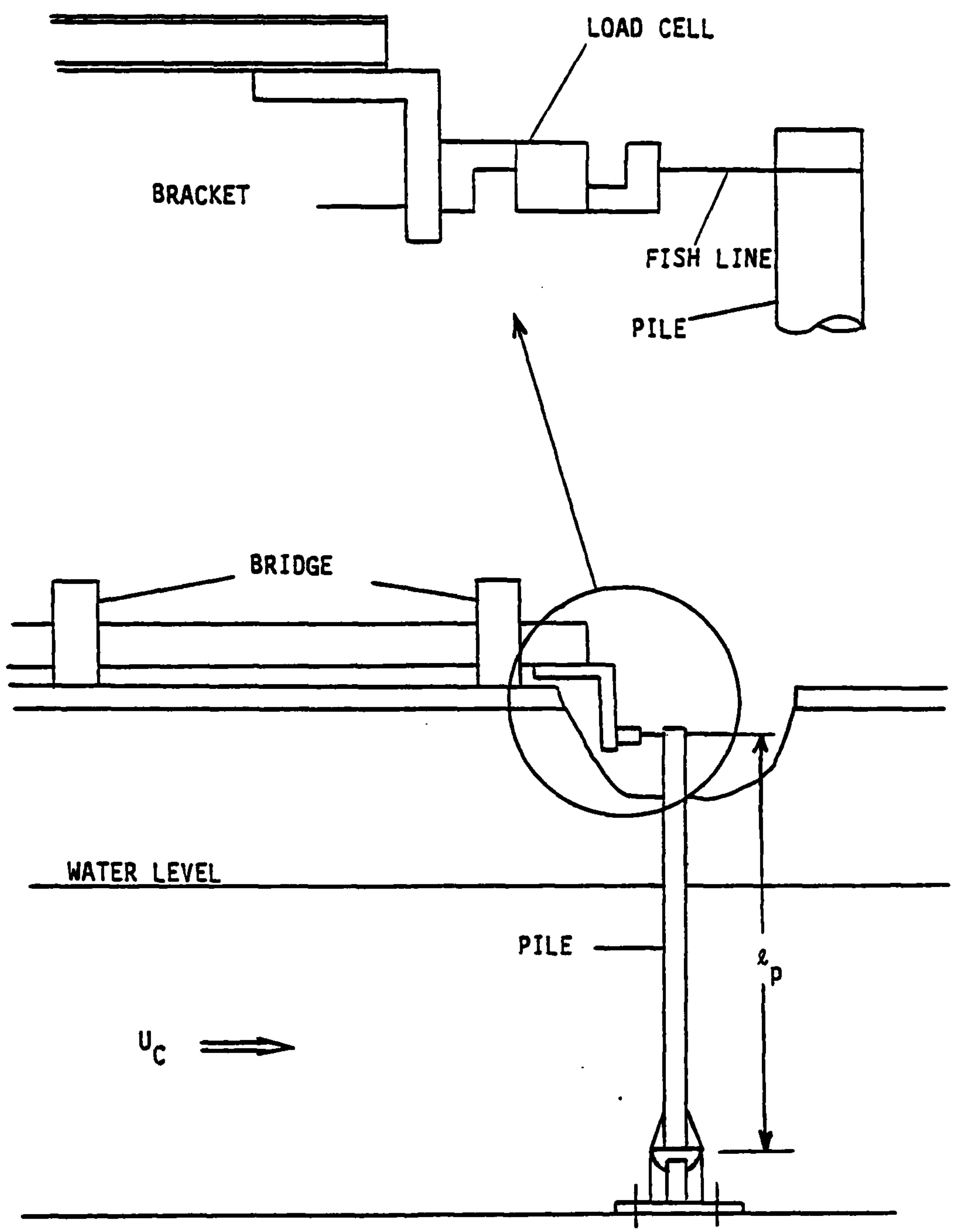


Fig. 17. Circulating Water Channel setup for hydrodynamic moment vs. speed experiment. Upper schematic shows details of load cell - pile arrangement.

distance from the longitudinal I-beam bracket (see Fig. 16) on the bridge structure to the top of the pile was recorded. This value was considered a reference value (d_{ref}) indicating the vertical position of the pile.

The water speed was increased to a value in the range listed above and a steady state was allowed to develop. The speed was then measured along with the horizontal distance (d_h) from the pile top to the bracket. The angle was determined by:

$$\frac{d_h - d_{ref}}{\ell_p} = \tan\theta \tag{14}$$

where d_h and d_{ref} are as defined above and ℓ_p is the distance from the axis of rotation to the top of the pile (as shown in Fig. 16). This procedure was repeated at different speeds until the upper limit of the water speed range was achieved.

<u>Hydrodynamic Moment Measurements</u>

In the second experiment the hydrodynamic moment (M_C) due to U_C was measured. The pile base plate remained secured to the CWT test section bottom. The fore and aft stays were disconnected allowing unrestrained pile rotation in the direction of the flow. A load cell was bolted to the bridge bracket, as shown in Fig. 17, fixing one end of the load cell. The action end of the load cell was then connected to the top of the pile with a piece of light nylon line. The pile was moved to a vertical position and the nylon line secured. The location of the line on the pile relative to the axis of rotation was recorded. The water speed was then increased as in the previous experiment and the value of the force was recorded for each U_C. The load cell used in this experiment was the same one used in the bench testing. The distance ℓ_p times the force yielded the hydrodynamic moment (M_C) due to the uniform current U_C.

RESULTS

The results from the angle vs. current experiment are plotted in Fig. 18 where current speed is provided for both the model scale and full scale. The main point to note here is the low value of the angle at maximum U_C. The angular displacement of the pile is less than 1 deg from the vertical at the maximum current. This is well within the verticality limit specified in the design criteria. From this perspective the experiment was highly successful and demonstrated the integrity of the design concept of high initial stiffness to maintain verticality under environmental loading.

The computer model PILESTIFF was used to estimate an effective stiffness for the test conditions. It was found that the effective k_1 during the trials averaged about twice the design value. Thus in-water performance was found to be better than both theoretical predictions and bench tests.

Hydrodynamic moment measurements were used to estimate the drag coefficient, C_w, and to compare this with the C_w values assumed in the initial computer modeling. The drag coefficient was determined using the following equation,

$$C_w = \frac{F_C}{\frac{1}{2}\rho_w U_C^2 A_p} \tag{15}$$

$$= \frac{M_C(d/2)^{-1}}{\frac{1}{2}\rho_w U_C^2 (d_p d)}$$

and results are plotted in Fig. 19. There is some variability in the C_w values determined, but all points (with average = 0.886) are less than the value of $C_w = 1$ used in the computer models.

During both experiments observations were made regarding the lateral motion of the pile. Lateral motion is considered the motion perpendicular to the flow direction which is induced by vortex shedding. The observed lateral motion was very limited, approximately 1/16 inch peak to peak at $(U_C)_{max}$ as determined by a hand held scale.

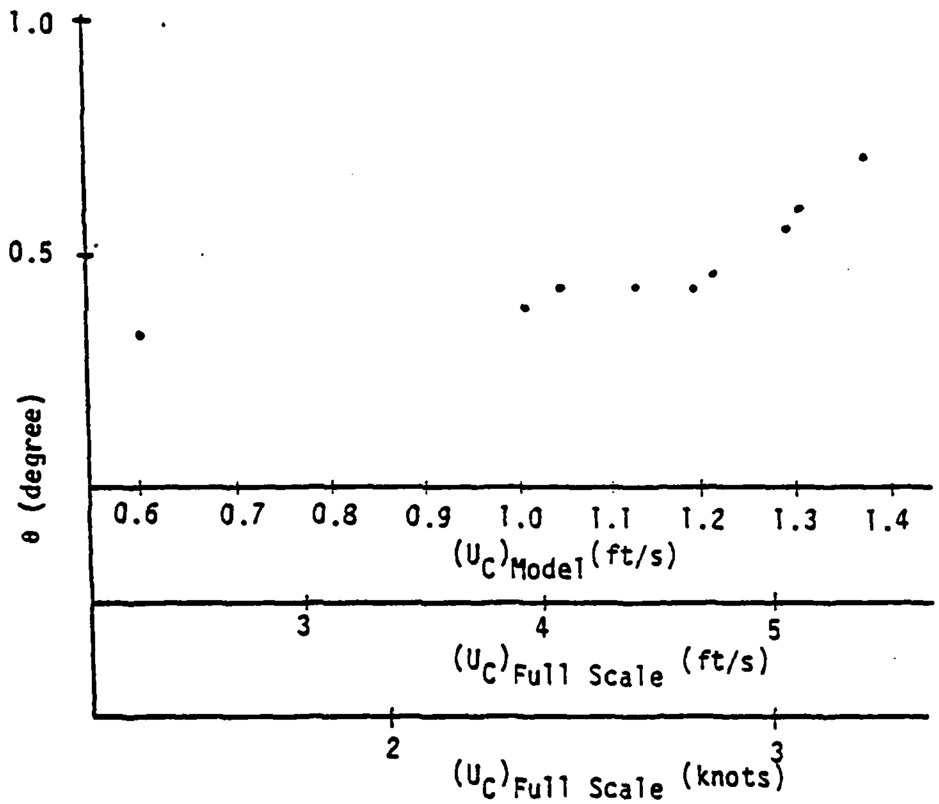


Fig. 18. Results of the angle vs. speed experiment. Maximum angle (θ max.) corrected for wind using OPPILE (60 knots scaled) is 2.23 deg which is less than the most restrictive design criteria.

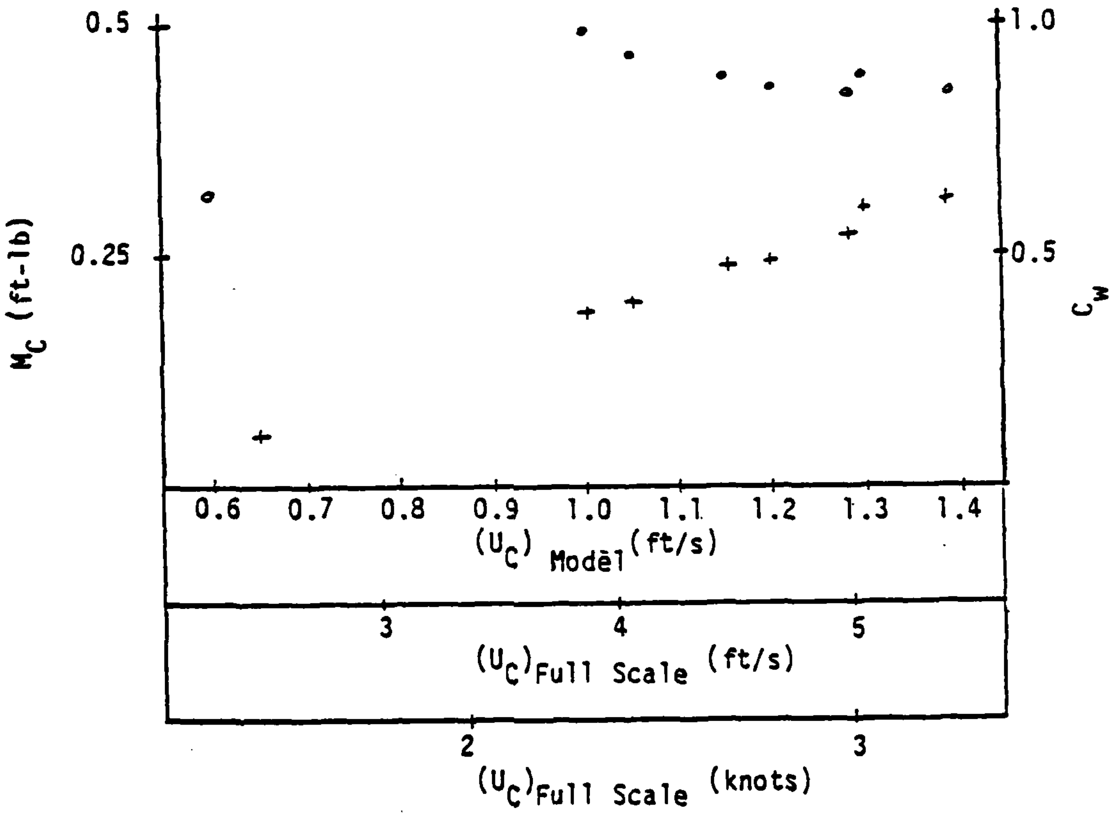


Fig. 19. Results of the hydrodynamic moment vs. speed experiment. Shown are the hydrodynamic moment M_C(+) due to current and the drag coefficient C_W(o).

The results of these experiments were encouraging. The ability of the model to provide the sufficient initial stiffness under the maximum uniform current condition indicated the concept is an achievable solution to the design problem. The drag coefficient determined was conservative with respect to the assumed value used in the theoretical work. Finally, the behavior of the model with respect to vortex excitation was minimal.

VII. BARGE-PILE COLLISION EXPERIMENTS

OBJECTIVES

The objectives of the experiments, performed at the UNH indoor pool, were twofold. The primary objective was to qualitatively observe and record the impact processes with movies and still photography. The important point to observe was the return of the pile to a vertical position after the collision. The second objective was to measure the impact forces thereby quantifying the collision. This required instrumenting the barge with load cells and recording the data in a permanent form.

FACILITIES, INSTRUMENTATION AND PROCEDURES

Facilities

The UNH pool is 75 ft. long with an approximate depth of 4 ft. along its shallow edge. Thus a platform had to be constructed. When the pile base was attached to the platform, the proper amount of the pile (2 ft.) was below the ambient waterline. The platform was placed approximately 50 feet from one end, as shown in Fig. 20, to allow room for bringing a scale model barge up to speed before the collision. The pile was secured to the platform with the upper hinge axis oriented to be the axis of rotation during the collision with the barge.

The barge was a wooden vessel constructed in-house. Water was used for ballast, and the barge was partitioned to reduce the effect of sloshing. When the barge was entirely filled with water, the (maximum) draft was 0.75 ft. (11.25 ft full scale). The forward compartment was left dry for housing the impact instrumentation.

The barge was pulled through the water by means of a hand reel to wind up a tow rope. The 50 ft. of unobstructed travel was sufficient for the barge to come up to a steady speed which was measured by timing the barge as it passed over the platform.

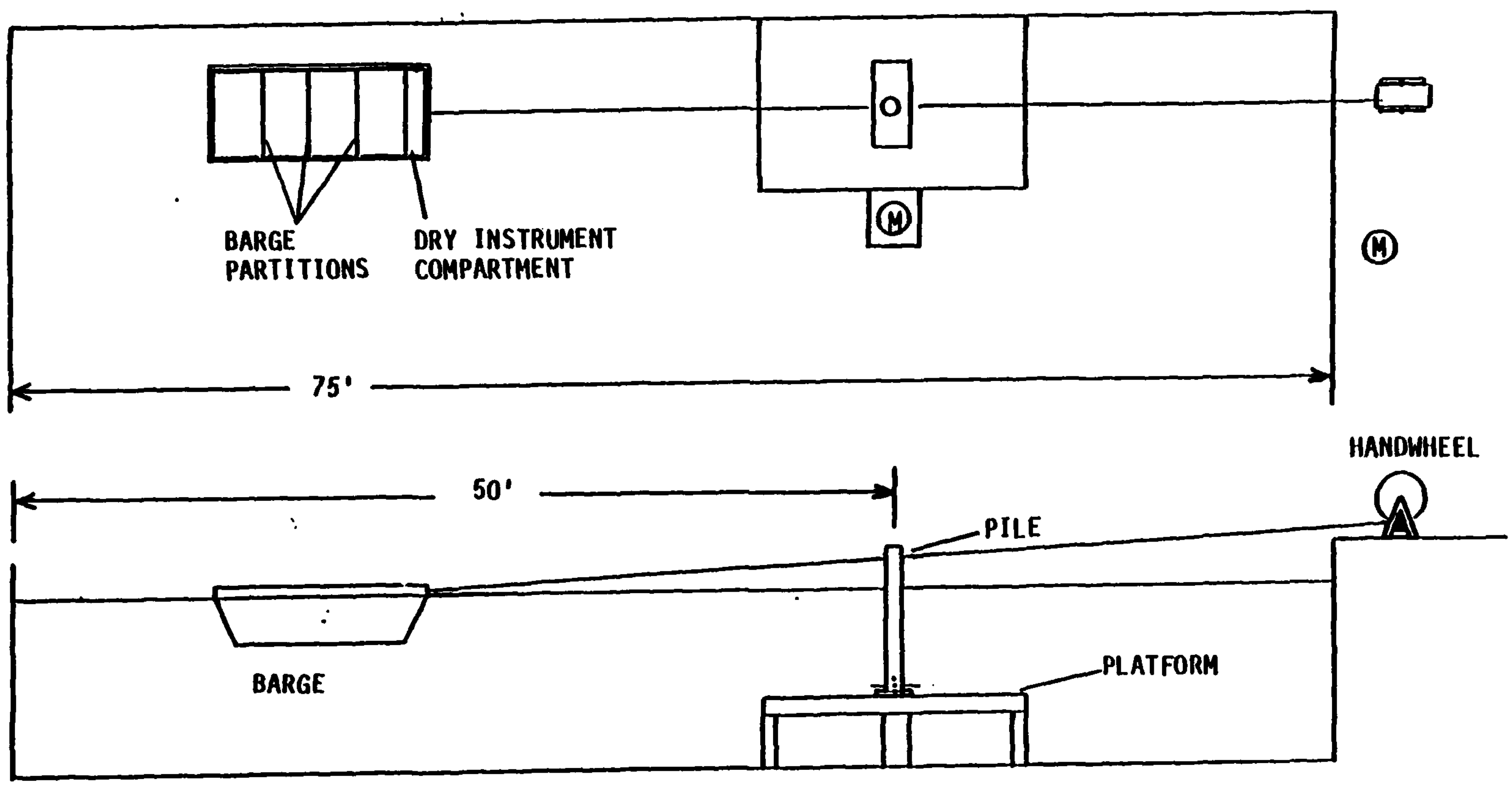


Fig. 20. Barge-pile collision experiment set-up at the UNH pool.

Photography

Movies and still photos of the collision process were made both above and under water. A movie camera enclosed in an underwater housing was located on the platform directly across from the pile hinge with the film plane parallel to the plane containing the barge velocity vector and the pile. The camera was also mounted above water at an angle to the barge direction to film the upper collision. The movie camera locations are designated by M on Fig. 20. The photography was completed with a set of still exposures taken from several locations both above and below the water.

Impact Force Instrumentation

Impact instrumentation included force sensors consisting of two cantilever beam load cells which were fabricated by the project team. Strain gages were attached to the upper and lower surfaces to measure the axial strain. The load cells were essentially two active arm transducers as shown in Fig. 21. The bridge excitation and output were monitored with a Validyne CD-19 carrier demodulator. The load cells were connected to the CD-19, and the system was fine tuned and calibrated.

The load cells were mounted inside the dry compartment in the barge bow area at two locations (see Fig. 22) of importance in the collision process. One was positioned to sense the upper impact (location A), and the other was set to sense the lower impact (location B). Carriage bolts were threaded into the free ends of the beams and allowed to extend through holes to beyond the outer surface of the barge. The bolt heads were covered with a flexible membrane to prevent flooding of the compartment. The load cells were oriented in a manner to sense the perpendicular component of the impact force as indicated in Fig. 22.

A lightweight aluminum bumper system was added to the collision zone of the barge to insure that the impact was recorded as it would be difficult to hit the bolt head alone during the collision experiments. The lightweight bumper system,

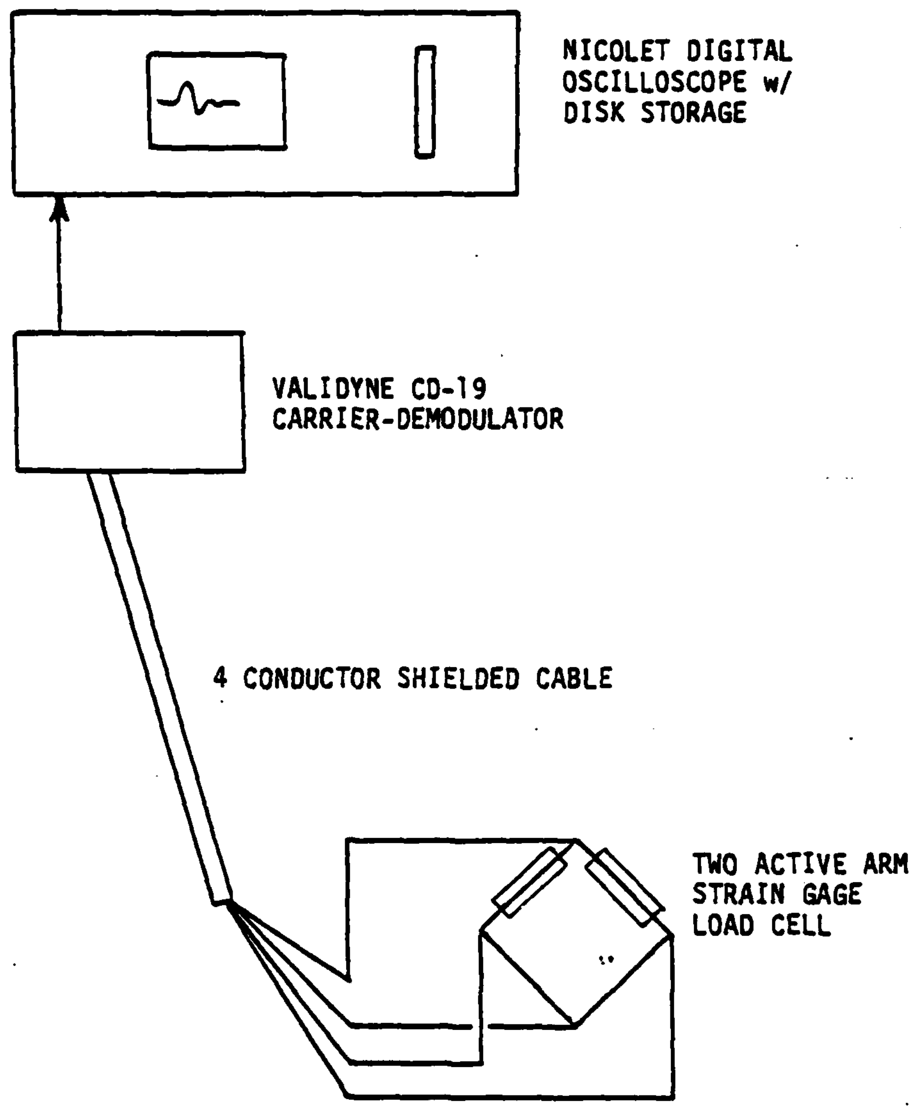
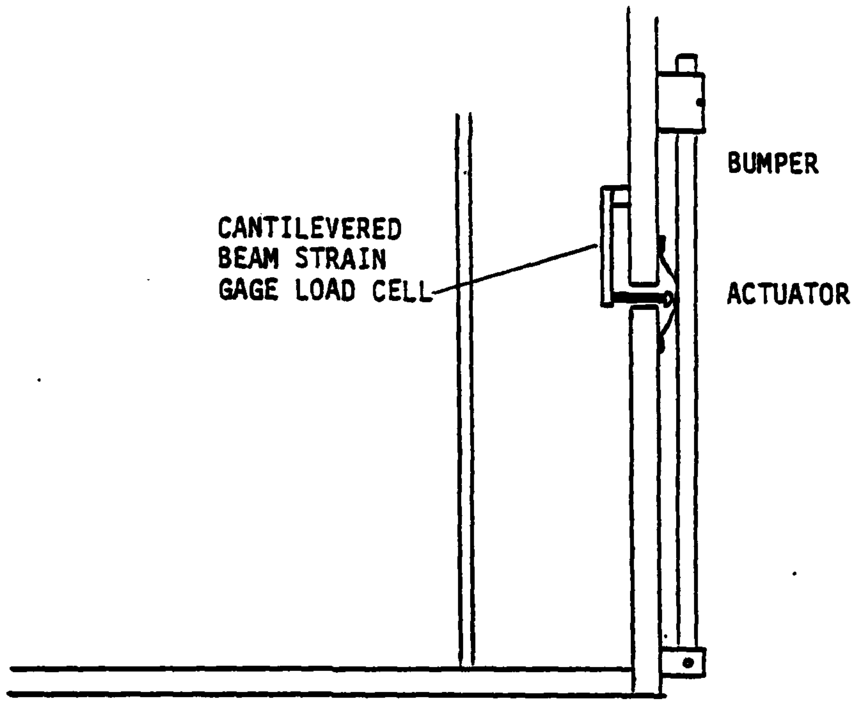


Fig. 21. Schematic of impact force measurement system. A two active arm strain gage load cell is coupled to a signal conditioning device (CD-19) whose output is displayed and stored on the digital storage oscilloscope.



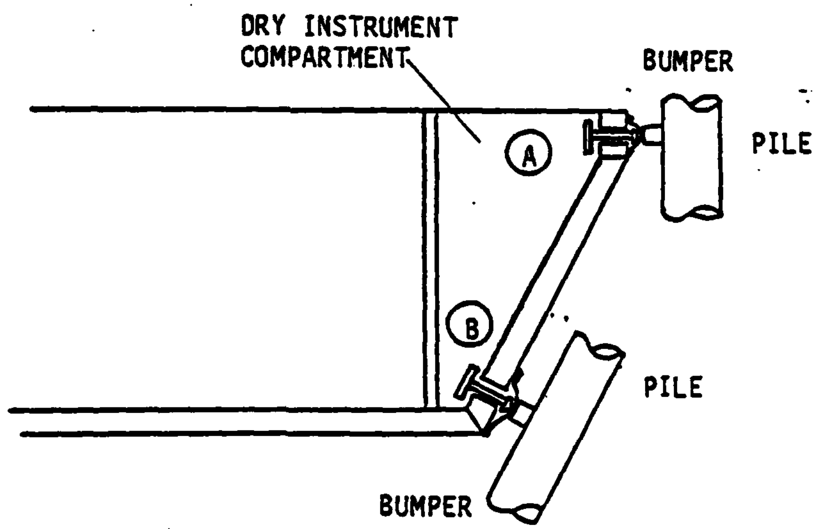


Fig. 22. Detail view of the barge load cell - bumper system for impact force measurement. Shows the pile-load cell bumper system action is perpendicular. Location A is the upper impact and location B is the lower impact.

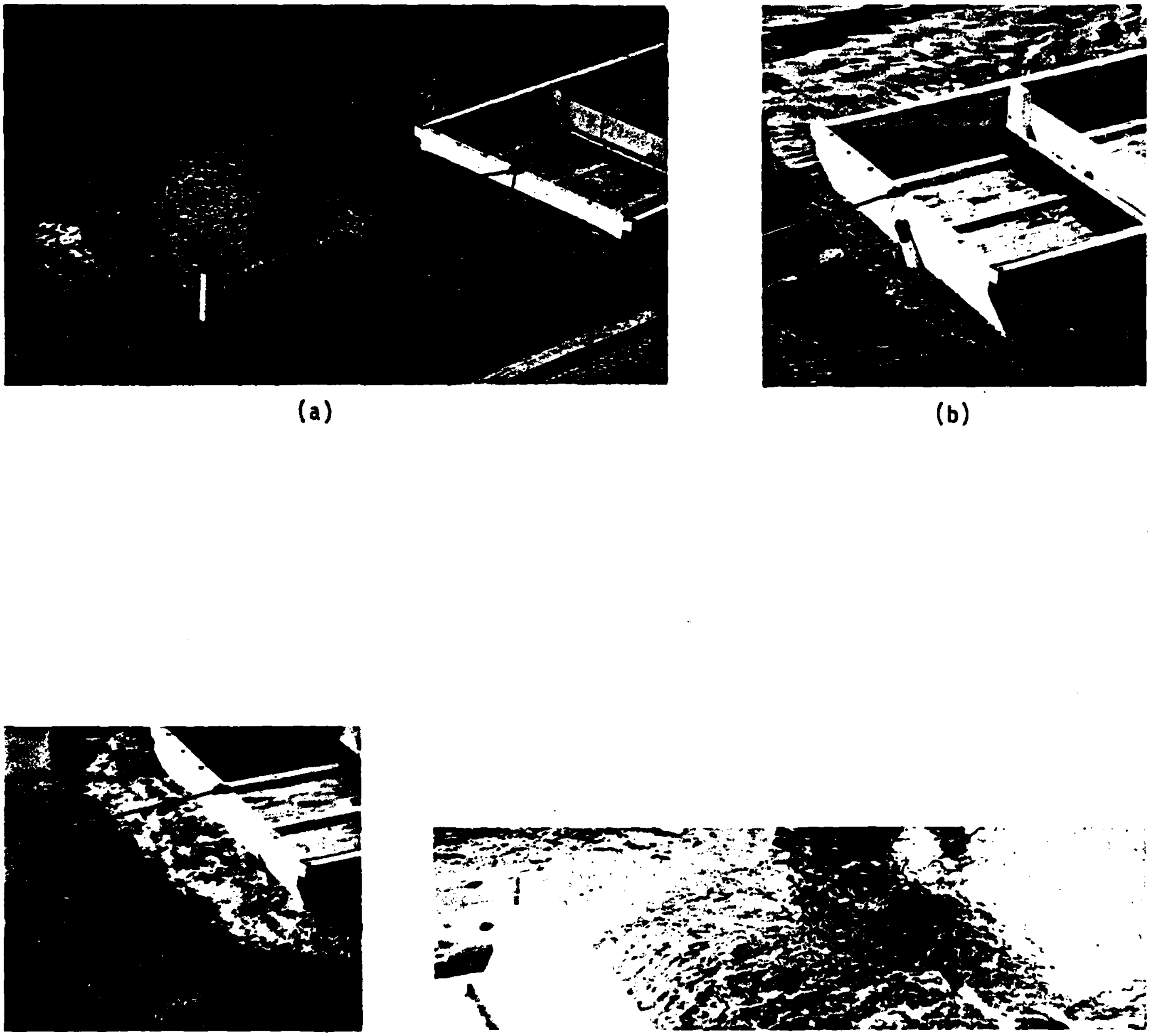
shown in Fig. 22, consisted of a pivot point, located as far as possible away from the bolt head actuator, an aluminum bumper and a bracket to hold the free end of the bumper in position and still allow movement in the desired direction. In practice the angle of bumper rotation is small, and the point of impact is very close to the bolt head. Thus the impact force on the bumper was essentially the same as that affecting the actuator-load cell.

Recording the impact force time series required more instrumentation. A means of acquiring the signals from the load cells had to be configured. As mentioned earlier, the load cells were calibrated in a system incorporating a Validyne CD-19. The recording system essentially added a Nicolet 2096 digital oscilloscope with disk storage to complete the measurement system as shown in Fig. 21. The electronics was set on a cart next to the pool side and connected to the load cells with a short shielded cable. The cart was moved along at the same rate as the barge allowing a minimum amount of shielded cable to be used. The oscilloscope was set for manual trigger and was triggered just before the collision thus digitally recording the impact forces. The oscilloscope memory was subsequently transformed to the floppy disk creating a permanent record of the event. This data and the barge velocity allowed for a quantification analysis of the collision process.

RESULTS

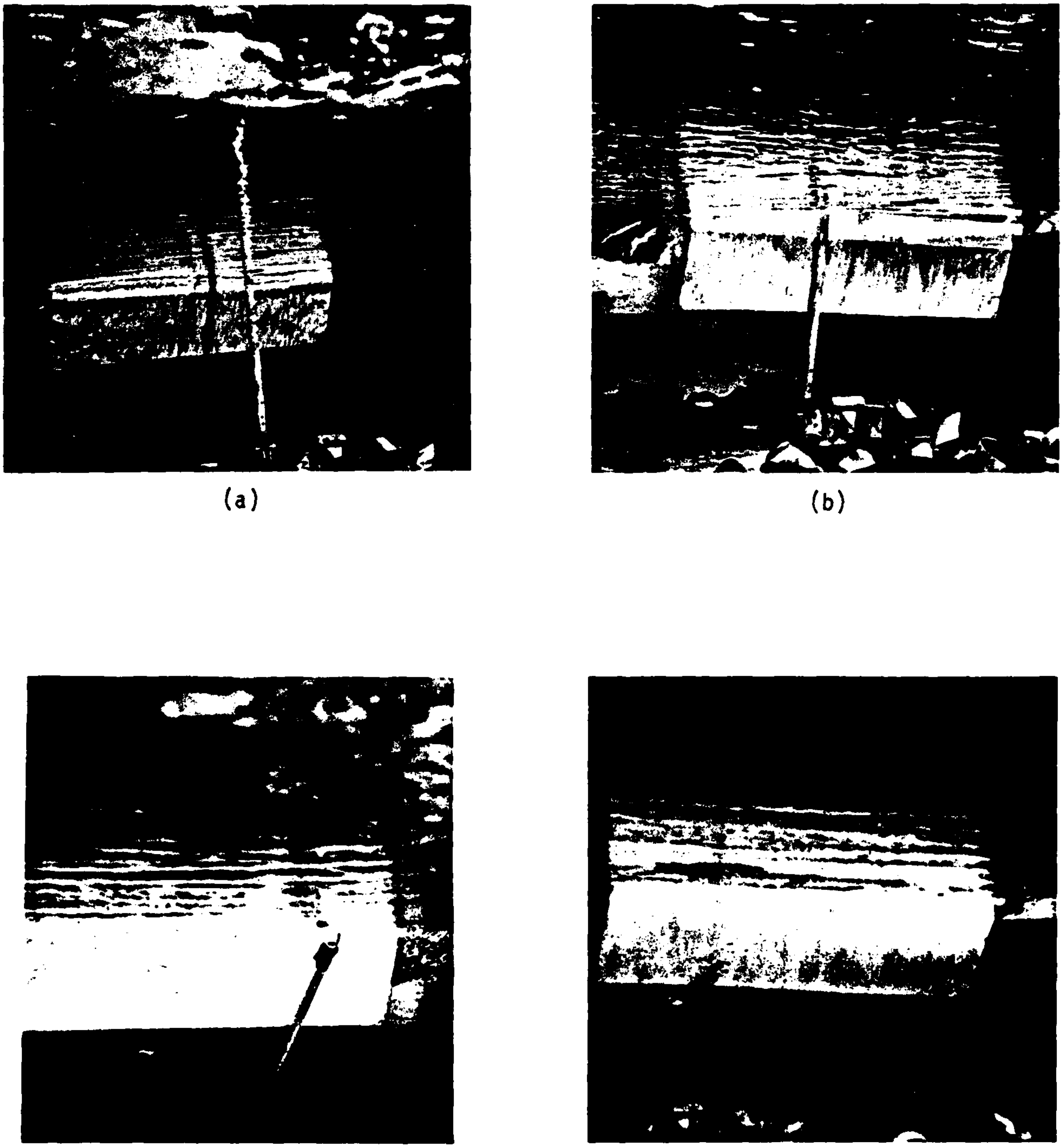
Observational

Important results are obtained directly from observations. The experiments showed that there is no physical damage to the model during impact and that it returns to a vertical position after the collision. This process is documented on two films submitted to the Coast Guard R&D Center at Avery Point, CT. The still photographs presented here in Figs. 23 and 24 illustrate the four steps in the collision process: 1) upper impact, 2) movement of the pile along the bow, 3) lower impact and 4) the movement of the pile along the barge bottom and ultimate



(a) (b) (c) (d)

Fig. 23. Barge-pile collision sequence as photographed from pool side Photo (a) is the approach, (b) is the upper impact (c) is the lower impact and (d) is the recovery after the collision.



(a) (b) (c) (d)

Fig. 24. Barge-pile collision sequence as photographed below the water surface. Photo (a) is the approach, (b) is the upper impact, (c) is the lower impact and (d) is the pile moving under the barge.

return to a vertical position. The most important observation to be made is that the system works (at the model scale) as designed. It returns to a vertical position after the collision with no physical damage.

Impact Force Measurements

Plots of typical upper and lower impact traces are shown in Fig. 25. The upper impact time series is truncated at approximately 7 lbs. This is due to the bumper coming up against a mounting bolt head which restricted its motion. A sine wave was fitted to the remaining correct data to allow the peak value to be estimated. Knowing the peak value and when it occurs is important due to the nature of the impact process.

The impact is considered to have started at $t = 0$ and continues until the time when the force reaches its peak value. This represents the barge hitting the pile over some finite time interval during which the load cell deflects to its maximum excursion. At this time, the pile contact point has accelerated to the barge speed, and the impact is over. After this time the pile commences to move away from the barge, and the load cell is "released" and rings until the no load state is again reached. Thus only the time until the maximum deflection is considered the impact.

From the time series of the impact events, the integral of force over time ($\int F_B(t)dt$ = force impulse) was calculated for both the upper and lower impacts. The upper impulse is 0.124 lb-s and the lower impulse is 0.306 lb-s. COLPILE was run for model conditions and the following impulse results were obtained: upper impulse, 0.131 lb-s and lower impulse, 0.236 lb-s. These results are within 23% at the largest discrepancy, indicating that the COLPILE program is as useful as a design tool.

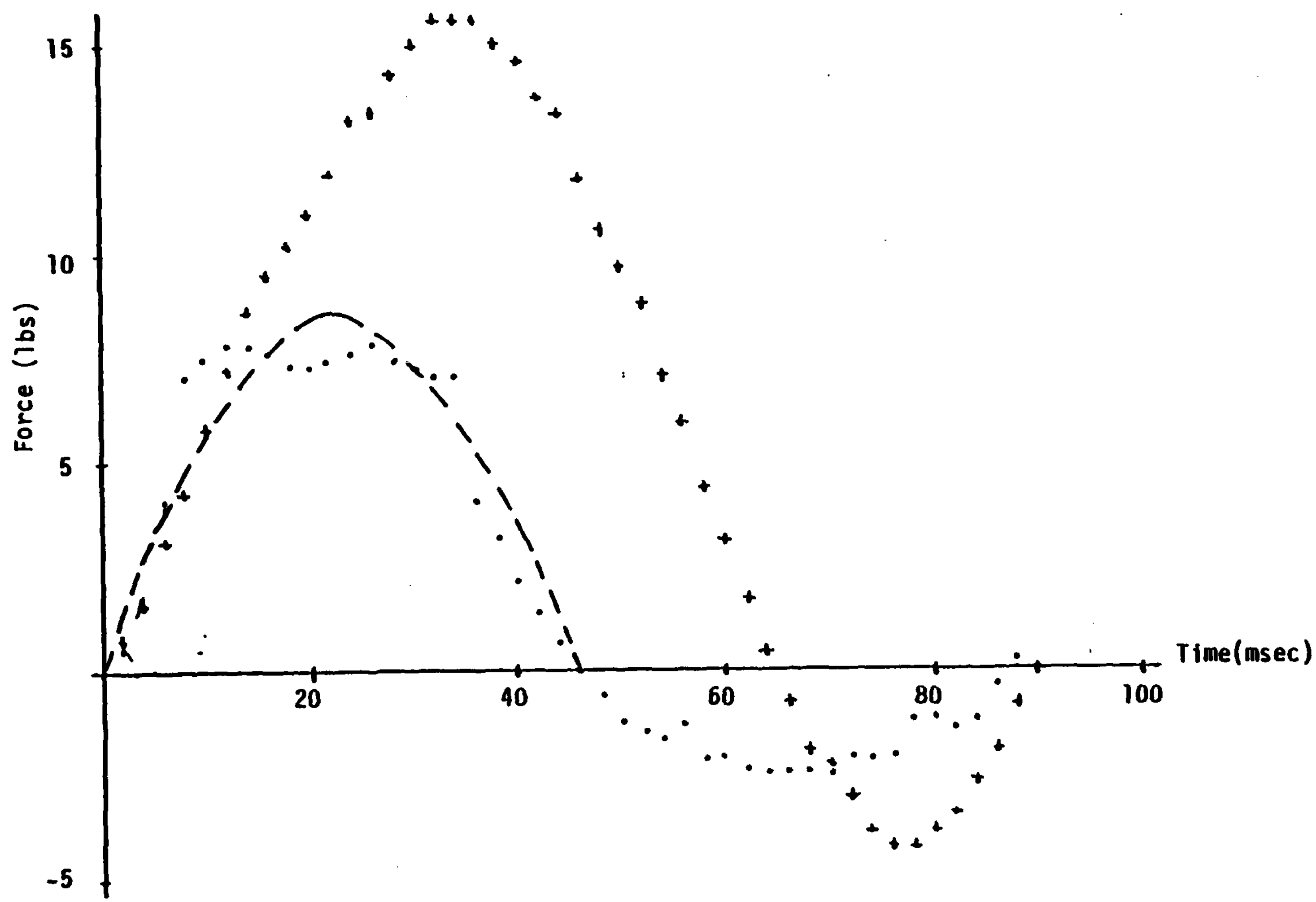


Fig. 25. Plots of the impact time series for the upper and lower collision points. The upper impact is denoted by (·) and the impulse is 0.1237 lb-sec and the lower impact is denoted by (+) and the impulse is 0.306 lb-sec. The curve denoted by the dashed line is a sinewave fit of the upper collision time series data.

VIII. COMPUTER MODEL APPLICATION TO FULL-SCALE PROTOTYPE

PARAMETER SELECTION

The computer models were applied to the CTPS design to estimate its full scale performance. Linear dimensions for computer program input were obtained directly from Fig. 6. Other model parameters were specified taking into account the results of the physical scale model experiments. Environmental conditions simulated - operational, hurricane and collision - were selected to conform to the design conditions referred to in Tables 2-4. Input to the models is summarized in Table 6.

The hinge initial stiffness coefficient k_1 was specified as the design value of 577,000 ft-lbs/rad, and the breakpoint angle was set at 10 deg. The bench and water channel tests indicated that this choice of stiffness is clearly achievable. If the actual k_1 is larger than the computer model k_1, which the experiments suggest is possible, verticality performance will be improved. Hence the k_1 specified is a "worst case" value. When the actual k_1 measured in the moment/angle tests approximated the computer model value, k_2 was about 1/20 k_1. This ratio was therefore employed in specifying k_2 for the computer simulations. Though negative k_2's were observed when the initial stiffness was much greater than the computer model value, the resulting large angle hinge moments still were approximately the same as those calculated using the k_1, k_2 combination specified here.

Pile drag coefficients inferred from the water channel tests were all slightly less than unity. Thus a somewhat conservative value of 1.0 was chosen for the simulation. From ideal fluid flow theory, the added mass coefficient should be 2.0. This was increased to 3.0 to include the additional effective pile mass due to flooding of the hollow pile.

Table 6. Parameters for full scale prototype modeling.

Parameter	OPPILE High Water	OPPILE Resonant	OPPILE Low Water	HURPILE High Water	HURPILE Storm Surge	COLPILE/RECPILE Typical Barge
Drag coef. of boards		1.28				
Drag coef. of pile		1.0		1.0		1.0
Added mass coeff. of pile		3		3		3
k_1		577,700 ft-lbs/rad		577,700 ft-lbs/rad		577,700 ft-lbs/rad
k_2		28,900 ft-lbs/rad		28,900 ft-lbs/rad		28,900 ft-lbs/rad
Breakpoint angle		10 deg		10 deg		10 deg
Load weight		1,744 lbs		1,744 lbs		1,024 lbs
Pile weight		2,890 lbs		2,890 lbs		2,716 lbs
Pile length (l_p)		40.7 ft		40.7 ft		38.25 ft
Pile diameter		1.5 ft		1.5 ft		1.5 ft
Length to load (l_m)		8.84 ft		8.84 ft		12.07 ft
Length to boards (l_b)		37.5 ft				
Area boards		36 ft^2				
Depth to hinge (d)	27.5 ft	27.5 ft	7.5 ft	27.5 ft	36.5 ft	25 ft
Total depth (d_t)	30 ft	30 ft	10 ft	30 ft	39 ft	30 ft
Wind velocity		60 kts = 101.3 ft/s		100 kts = 168.8 ft/s		
Current velocity		3 kts = 5.063 ft/s		3 kts = 5.063 ft/s		
Wave height		5 ft		6 ft		
Wave period	5 s	2.8 s	5 s	5 s		
Wave length	118 ft	41 ft	82 ft	118 ft	123 ft	
Static angle	5.0 deg	5.0 deg	4.2 deg	4.3 deg	3.8 deg	
Natural period		2.83 s		2.83 s		2.52 s
Barge speed (U_b)						10 kts = 16.88 ft/s
Length (L)						180 ft
Freebard (f_b)						0
Bow angle (θ_f)						25 deg
Draft (d_b)						12 ft

OPPILE and HURPILE were used to model operating and storm environments, respectively. OPPILE computer simulations were conducted for high water/design wave, high water/resonant wave and low water/design wave conditions. For each wave forcing, the computer simulation was run beyond the point for which initial transients had completely decayed (after 3 wave periods) in order to evaluate the regular, periodic response. Motion about the lower hinge was considered since this presents the largest projected area and is therefore the "worst cast" for wave/current loading.

COLPILE and RECPILE were used to estimate the pile response to a direct barge hit at the design speed of 10 kts. Motion about the upper hinge was simulated here because it represents the "worst cast" for barge clearance and hence impact loads. In a representative simulation, a barge bow angle of 25 deg and a draft of 12 ft were used since these values are typical of barges using the Houston area ship channel. To determine the effect of hinge clearance on impact loads, an additional series of COLPILE runs were made for the possible range of barge drafts.

PREDICTIONS

The OPPILE computed, steady state response time series for each of the 3 operating condition cases considered are shown in Fig. 26. The motion due to the resonant wave excitation, as expected, has the largest amplitude but does not exceed the maximum allowable verticality limit of 10 deg. At the other extreme, the low water response is much reduced and less regular due to weaker wave forcing. Hinge moments necessary to maintain the less stringent of the verticality criteria are seen to approach 100,000 ft-lbs.

The HURPILE calculated steady state response for the hurricane design conditions are shown in Fig. 27. Predicted average angular position is somewhat less and maximum angle amplitude does not greatly exceed that predicted for

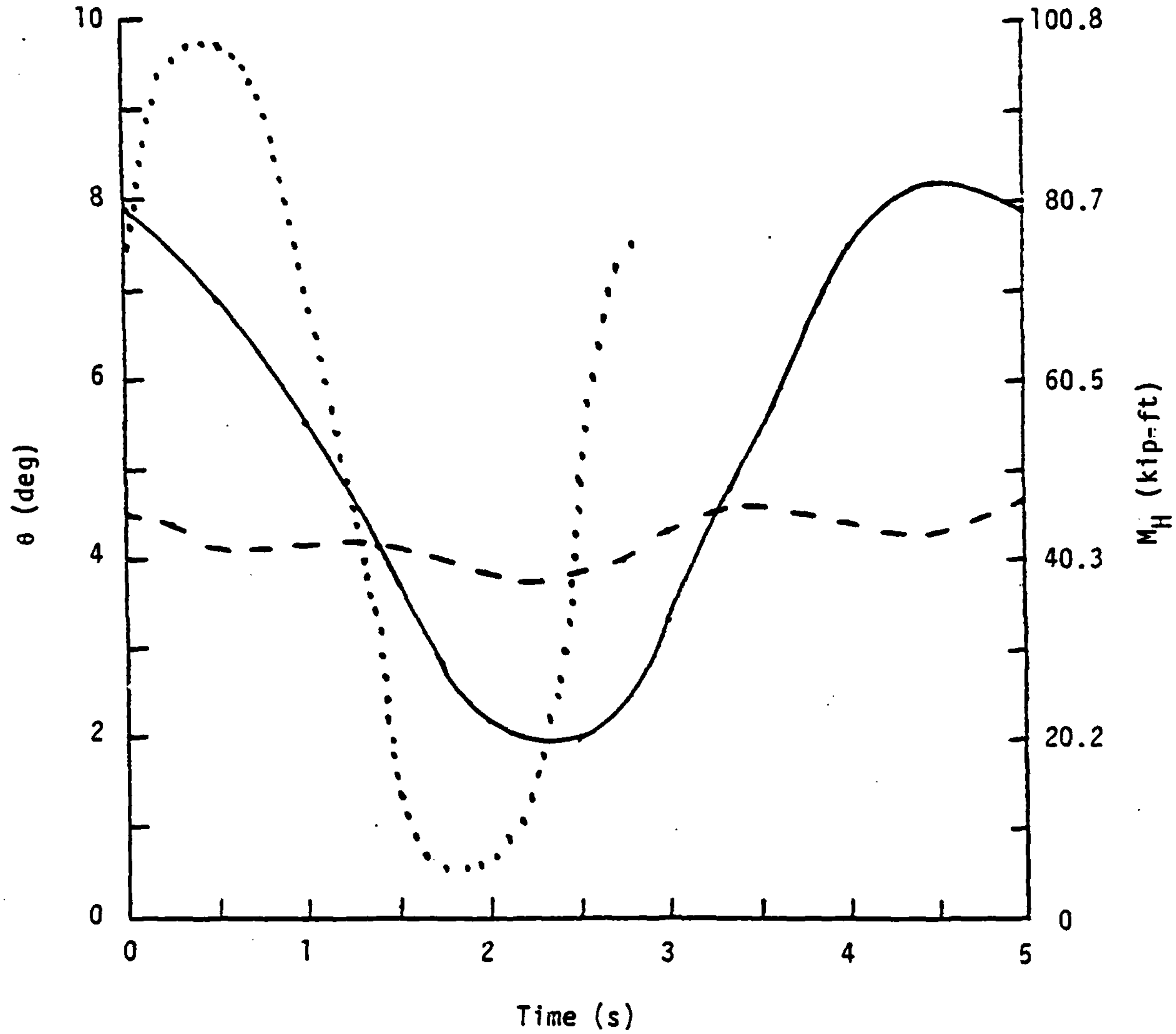


Fig. 26. Pile motion during operational conditions. Shown is the steady-state response over a wave period as computed by OPPILE. Plotted are response for high water (30 ft. depth, 5 s wave period) conditions (-), resonant (30 ft. depth, 2.8 s wave period) conditions (...), and low water (10 ft. depth, 5 s wave period) conditions (--). The time scale starts at the passage of a wave crest.

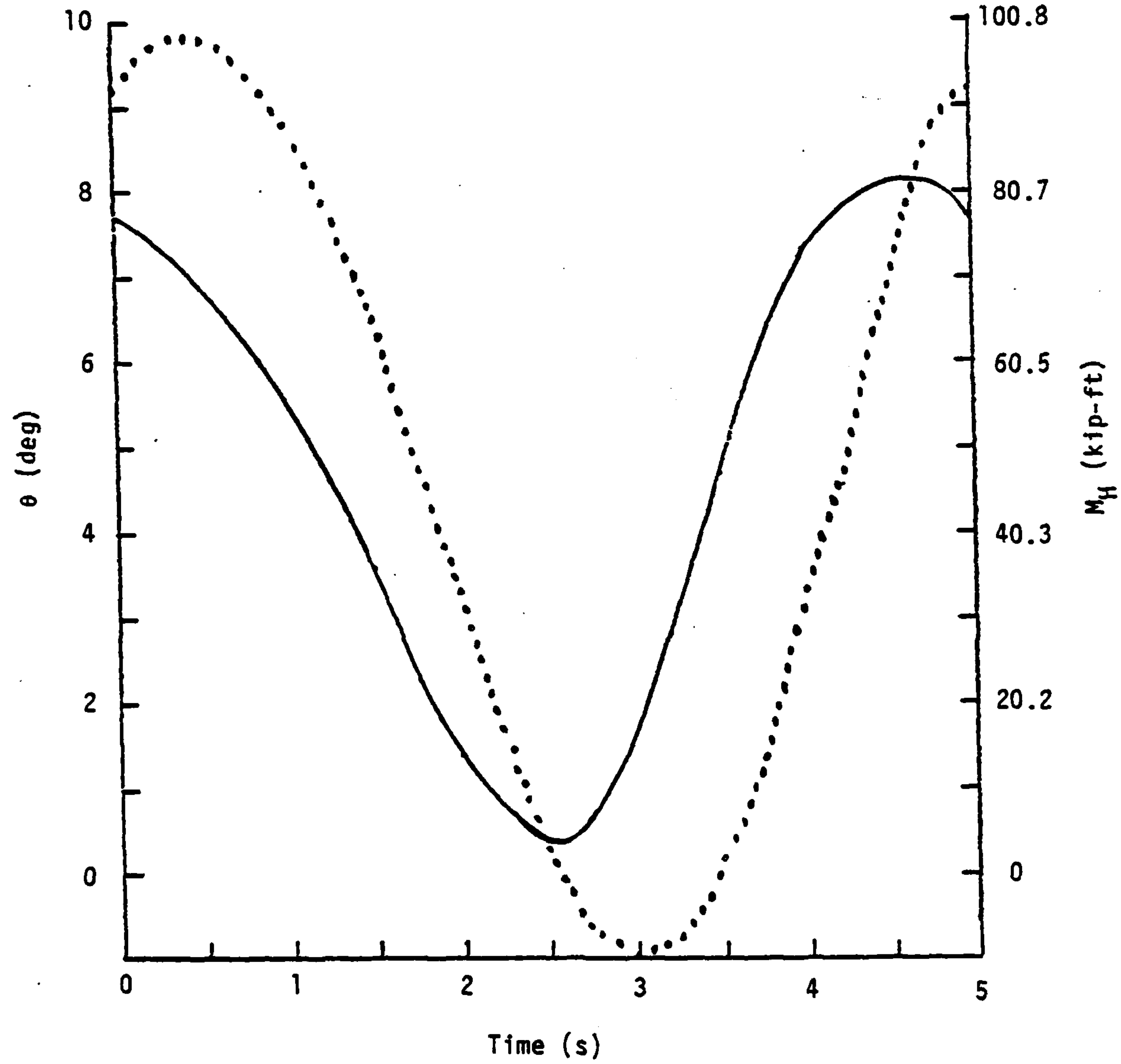


Fig. 27. Pile motion during hurrican conditions. Shown is the steady-state response over a wave period as computed by HURPILE. Plotted are response for normal high water (30 ft. depth) conditions (-) and storm surge (39 ft. depth) conditions (...). The time scale starts at the beginning of a wave crest.

operating conditions. This is explained largely by the decrease in forcing accompanying the sacrifice of the daymark boards.

Results calculated by COLPILE for the "typical" barge collision are given in Table 7. Hinge moment and reaction force loads in general seem reasonable, but the force impulse at the bottom of the bow rake actually represents very large impact forces due to the short duration of the impact process. Fig. 28 shows how the lower bow rake, barge force impulse becomes even larger with further decrease in clearance. These results suggest that it will be difficult to avoid local pile or hinge damage for clearances with respect to the hinge less than 7 ft unless special shock absorbing cladding is employed.

Pile motion during recovery from the design barge collision, as computed by RECPILE, is shown in Fig. 29. Returning to the vertical takes less than 10 s. The small overshoot and oscillation about the equilibrium point is quickly damped.

In general, it is seen that CTPS design easily satisfies the minimum design criteria for worst case operating and hurricane conditions. It does not, however, appear feasible to design CTPS systems to sustain barge collisions at very low clearance distances. With this single qualification, the predicted performance has been found to be entirely acceptable.

Table 7. Collision of "typical barge" with pile. Position and dynamic loads are computed by COLPILE. Time is given in s, θ in deg, moments in ft-lbs, forces in lbs. During impact, moment impulse (ft-lb-s) and force impulse (lb-s) are listed.

Time	θ	M_B	F_B	M_H	R_H	R_V
Impact at top of bow rake						
0	0	68,000	2,720		-850	0
.25	9.6	137,900	5,470	96,600	4,380	3,060
.50	18.7	124,300	4,730	105,200	4,340	3,940
Impact at bottom of bow rake						
.65	25.0	61,170	4,260		1,080	500
.75	28.5	189,000	12,840	110,200	12,970	7,050
1.00	41.0	157,300	9,180	116,400	9,490	9,320
1.25	50.0	137,200	6,810	121,000	6,620	9,690
1.50	56.6	81,500	3,470	124,300	3,580	7,990
1.75	61.5	62,700	2,310	126,800	2,270	7,080
2.00	65.2	57,600	1,870	128,700	1,600	6,530
2.25	68.1	57,400	1,650	130,150	1,220	6,160
Contact with barge bottom						
2.5-12.8	70.1	70,700	1,910	131,200	190	5,640

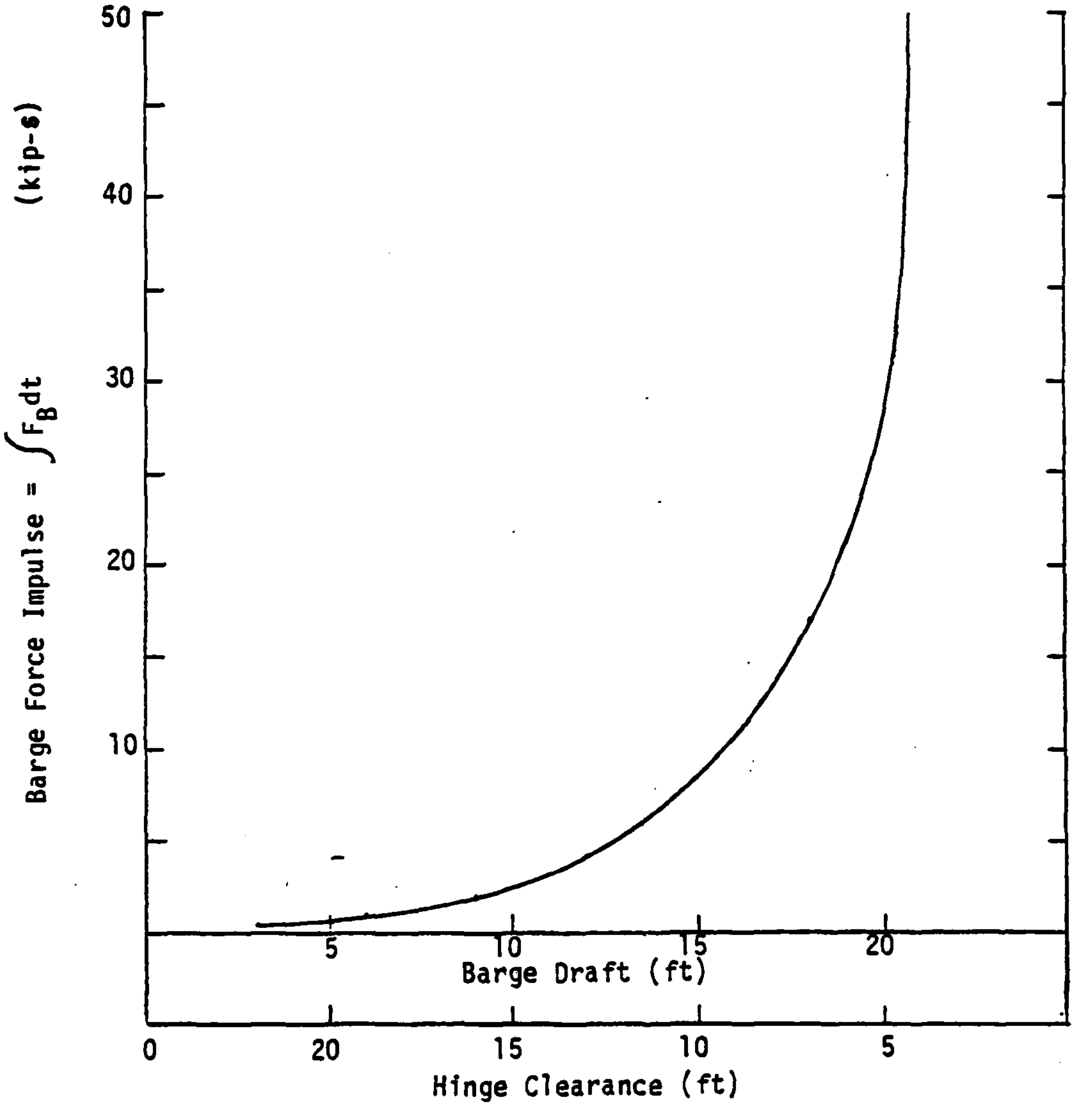


Fig. 28. Barge force impulse as a function of barge draft (or hinge clearance). Total water depth is 30 ft and hinge height is 5 ft.

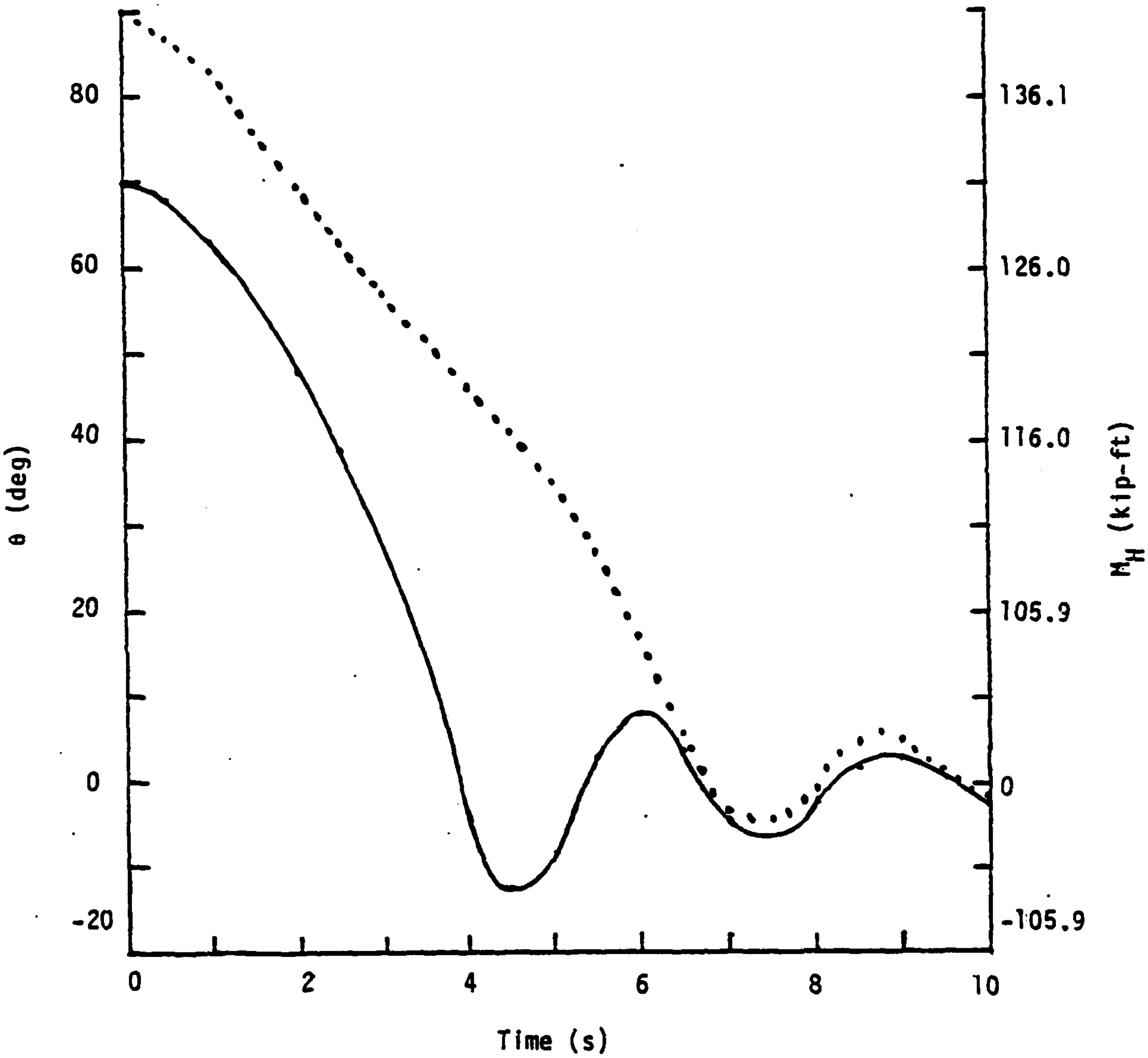


Fig. 29. Pile recovery as computed by RECPILE. Shown are pile recovery from a "typical barge" collision (—) and recovery from a 90 deg. knockdown in an adverse current of 3 knots (...).

IX. LOGISTICAL AND COST FACTORS

SOIL MECHANICS

The ability of the subbottom sediment to withstand the loading due to the impact process is crucial to the success of the CTPS system. The base must remain fixed in order for the design criteria to be met. What follows is a first order analysis of the soil mechanics problem which will provide sufficient information for practical design decisions.

The problem is that of a circular pile driven into the ocean bottom subjected to a laterally applied impact force. The conventional approach to laterally loaded piles, however, is a static analysis, and this method is used here. It is assumed that the sediment resistance varies linearly with depth from a value of zero at the sediment surface to a maximum value at the bottom of the pile. Using a graphical solution presented in Fig. 72 of Paules and Davis (1980), and assuming a typical value of bouyant density (total sediment density minus the water density) at 60 lb/ft^3 and a pile diameter of 1.5 ft, results for horizontal force R_H on a 30 ft and a 40 ft embedded pile section are 8,300 lbs and 11,900 lbs, respectively.

These forces are significantly smaller than an estimated hinge reaction force during impact of 27,000 lbs calculated using COLPILE and collision experiment results. Paules and Davis indicate that there are various design modifications for correcting this problem and effectively strengthening the pile system with respect to laterally applied loads. The basic concept inherent in all the schemes is to increase the soil bearing surface.

The most desirable solution is to add wings to the upper portion of the driven pile. The wings can be analyzed as retaining walls in a passive earth pressure case under undrained conditions. Employing the method presented by Lambe and Whitman (1969) and using 60 lb/ft^3 for bouyant density and 500 lb/ft^2 for ultimate shear, a lateral force of over 34,500 lbs can be sustained by a 3 ft wide by 5 ft. high rectangular wing. Four wings of this size could be added to

the upper portion of the driven pile to achieve more than ample resistance to the applied lateral load.

This analysis indicates that a stand alone single pile cannot withstand the laterally applied impact load. The addition of moderately sized wings, on the other hand, appears to be a technically feasible solution. More analysis concerning the site specific soil profile is necessary, however, and should be completed for each installation.

SURVEY OF HOUSTON AREA NAVIGATION AIDS

A survey was taken of the navigation aids in the Houston area to evaluate the extent to which existing markers are replacable by CTPS systems. The geographical region considered is the Houston Ship Channel starting at Point Bolivar and extending across Galveston Bay to Morgan Point. According to the Coast Guard "Light List" (1984), this area includes a total of 74 in-water, government navigation aids.

To determine which aids may be exchanged, criteria based on water depth were developed. It was assumed that a CTPS can sustain a collision at maximum speed by a fully loaded, typical barge (draft = 12 ft) if the fraction of water depth required for clearance is the same as in the design case. Since 5 ft for hinge height plus 7 ft to reduce impact forces provides a generous clearance in 30 ft of water, the minimum depth can be evaluated from

$$(7+5)/30 = [(d_t)_{min} - 12]/(d_t)_{min}. \tag{16}$$

Thus the minimum depth is $(d_t)_{min}$ = 20 ft. A maximum depth of 40 ft was chosen as an upper limit since the CTPS design can easily be scaled upwards by 1/3. The number of in-water government aids, including buoys, dolphins and piles, in the depth range 20 to 40 ft is 14.

This criteria may be relaxed if it is assumed that the aid is replaceable for depths in which the typical barge must simply clear the hinge itself. Since

the absolute minimum mud clearance for a 30 ft water depth is 6.5 ft., the less restrictive minimum depth criterion becomes

$$6.5/30 = [(d_t)_{min} - 12](d_t)_{min} \tag{17}$$

yielding $(d_t)_{min}$ = 15 ft. This criterion should be applicable if the barge does not hit directly at full speed or if the barge is not fully loaded. The number of in-water government aids (excluding skeleton towers) in the depth range from 15 to 19 ft is 22.

In summary, 14 out of 74 or 19% are replaceable using a criteria based on the maximum design collision condition with a typical barge. Nearly half (14 + 22 = 36 out of 74), however, are replaceable assuming that only minimum clearance for a fully loaded barge is necessary.

INSTALLATION PROCEDURES

Installation of the CTPS should not impose serious departures from present practices of installation and does not require the use of divers or sophisticated underwater equipment as required by the logistical design criteria given in Table 1. Use of an 18 inch steel pipe as piling is familiar to the Coast Guard since it is presently in use for ordinary pile structures. The hinge component can be pre-assembled on shore to reduce crew effort and vessel time during the actual deployment.

The total length of the pile system is 44 ft plus at least 30 ft below the hinge. The embedment length of 30 ft normally needed to obtain fixity in soft clay may, however, have to be increased because of the hinge impact loads transmitted to the base. Since the total length exceeds the 50 ft maximum length stipulated by requirement (b) in Table 1 (due to limited crane height), the pile must be installed in sections.

A scheme for dividing the CTPS into 3 parts is shown in Fig. 30. The above water part is attached via a flange coupling to the main pile which in-

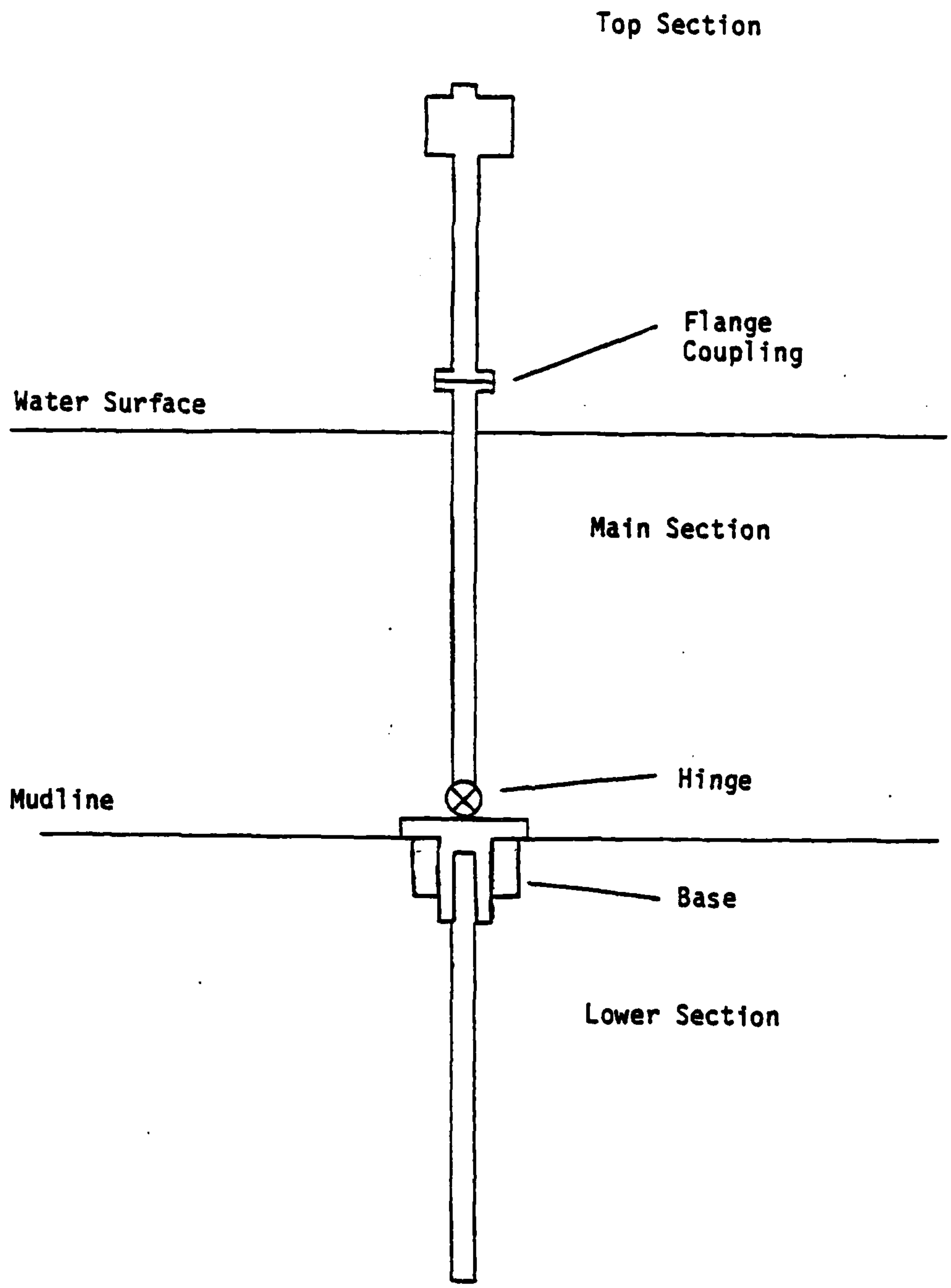


Fig. 30. Sectioning of the CTPS to expedite installation and removal.

cludes the spring, hinge and base. The bottom of the base consists of a tapered socket which fits over the top of the lowest section embedded in the soil. Gussets are used to reinforce the base/socket joint and to increase soil bearing area. The enlarged soil contact surface aids the embedded pile section in resisting base movement during collisions.

The installation procedure begins by driving the lower section until its top is just above the water surface. (Thus its length is governed by water depth and may be longer than that necessary to obtain fixity). Next the main pile member, complete with a full-length driving collar, is set in place and the socket joint secured by bolts. The fastening need not be extensive since the socket itself is designed to transfer the bending moment and compressive axial and shear forces to the lower section. The bolts are mainly a precaution against minor, inadvertent lifting which might occur during installation.

Using the collar to transfer the hammer blows directly to the base plate, the system is driven so that the base is level with the mudline. After driving, the (reuseable) collar is removed. Lastly the top section is attached, stay tension is adjusted and the navigation aid is built. For shallow areas, of course, the shorter CTPS sections could be joined on deck.

When removing the CTPS, the structure will separate at the base socket/lower pile joint. Thus the major portion of the system is recovered intact, and the remaining section is below the mudline. The bolting used to secure this joint during installation will, therefore, be done so that it serves as a weak point with respect to direct upward pull.

COST ESTIMATE

Cost estimates (materials plus fabrication) were made for the 3 major design components - the piping, the hinge/stay system and the "spring" element. Sufficient piping for both the section above the hinge and the embedded portion is estimated to cost $4,000. Hinge/stay system construction should total approxi-

mately $2,000, while "spring" costs may vary from $800 to $2,900 depending on the type of "spring" used.

Complete system costs will therefore be between $6,800 and $8,900. Using information supplied by Miller (1982), installation costs are approximately $4,000, so total costs range from $10,800 to $12,800. In comparison the total expense (pile plus installation) of a simple 12 inch wooden pile is about $4,500. Thus the CTPS approach would become cost-effective after 3 collisions.

X. DISCUSSION

CONCLUSIONS

Bench testing of the CTPS design developed in this study, performed out of water using the physical scale model, showed first of all that the hinge possesses the necessary kinematic characteristics. Full 90 deg from the vertical articulation is possible for all horizontal angles. Secondly the desired piecewise linear hinge moment as a function of angle behavior ($M_H = M_H(r)$) was observed. The scale model experiments indicated that the design initial stiffness coefficient $k_1 = 11.4$ ft-lb/rad (577,700 ft-lb/rad full-scale) can be achieved, the actual breakpoint angle occurs approximately at the design value of 10 deg, and normally $k_2 \cong 1/20\ k_1$. It was noted that, depending on the prestressed stay tension balance and internal friction, k_1 can exceed the design value though large angle hinge moments are not greatly affected. This increase in initial stiffness, however, enhances the CTPS operational verticality performance and is not viewed as detrimental.

Water channel experiments conducted at the Coast Guard Academy CWT facility showed that, at the model scale (1/15) the design easily meets the verticality requirement at the maximum current specified in the design criteria. Lateral movement due to vortex shedding was observed to be negligible. Measured effective drag coefficients for the pile in water were found to be less than 1 so that use of $C_w = 1$ for computer modeling purposes may be viewed as being conservative.

Collision experiments, using the physical scale model in the UNH indoor pool, showed that the CTPS design can sustain impact at the required (scaled) barge speed and recover to an upright position. Impact forces were measured, and force impulses were compared with predictions made using the computer models. Agreement was within 23% indicating the computer simulations are sufficiently accurate for design evaluation purposes.

Computer simulations were made for operational, hurricane and collision conditions using imput dimensions from the design itself, performance parameters found suitable from the physical model experiments, and environmental specifications required by the design criteria. The computer program OPPILE, developed to determine pile performance during operating conditions, showed that the design meets the maximum allowable verticality limit. The computer model developed for calculating pile motion during hurricane conditions, HURPILE, indicates that, since the daymark boards are sacrificed, pile movements and hinge moments are not large, and no damage should be expected. The programs developed for modeling collision processes, COLPILE and RECPILE, demonstrate that, for collisions at the design speed by typical barges used in the Houston area, damage to the pile itself should not occur and pile recovery is expected to be prompt. COLPILE does predict, on the other hand, that impact of the barge's bottom of the bow rake with the pile has the greatest potential for damage. This problem increases in severity with decrease in clearance. Because of the need for sufficient clearance and the height required for the hinge itself, the very severe mud clearance of 3 ft specified in the design criteria cannot be met. As noted above, however, there should be no difficulty with collisions by barge traffic of average draft.

Logistical requirements for the design were satisfied since installation procedures do not differ radically from existing practice. A method of installing the pile in sections was found to be suitable for meeting the pile length limitation of 50 ft. Costs for the design were estimated to fall between the design goal of $5,000 and the maximum allowable amount of $10,000. At this level of expense, a deployed CTPS will become cost-effective after three collisions.

At the present time, a 1/4 scale model is being built for field testing using Sea Grant funding. It is expected that this experiment will shed additional light

on many of the practical engineering aspects such as material selection, system fabrication and installation.

RECOMMENDATIONS

The pile system design developed in this study appears to be a feasible solution to the problem of pile damage in the nation's extensive high traffic, shallow waterways. Physical scale models and computer simulations indicate that the design is technically sound and preliminary cost estimates have shown that the concept is financially beneficial where the potential for collision is great.

We therefore recommend that the next step in development be taken in which a full-scale prototype is built and field tested. Construction plans for prototype fabrication should be based principally on the design presented in this report. Departures to conform to a particular installation location, of course, may be made. It is recommended, however, that design parameters be re-established using the design guidelines and computer models as well as the physical scale model data presented here.

In summary, the results obtained in this study are very encouraging. Continued development and subsequent implementation of working systems is recommended and promises eventually to save much effort and expense on the part of the Coast Guard.

AD-A155 485 THE DESIGN AND MODEL TESTING OF A COLLISION TOLERANT PILE STRUCTURE(U) NEW HAMPSHIRE UNIV DURHAM M R SWIFT ET AL. MAR 85 USCG-D-14-85 2/2

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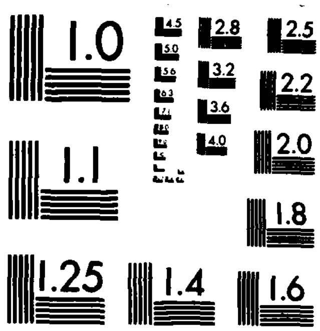

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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VII. APPENDIX A: COMPUTER PROGRAM LISTINGS

STATUS OF PROGRAMS

In this appendix program listings for the computer models described in Section II are provided. The programs are written in Applesoft BASIC and were originally used on an Apple IIe microcomputer with printer. The type and method of input, pre-set parameter values (changeable by editing), and output options are evident from the listings.

The programs are presented here as they exist at the time of the writing of this report (November 1984) though they are presently being upgraded. Anticipated changes include improving program efficiency and making the programs clearer to potential users. Though the programs are believed fundamentally correct, further verification studies are also planned. The authors would appreciate being informed of any "bugs" or errors found by others. Due to the transitional status of these programs, the authors cannot be responsible for their misuse. No warranty is expressed or implied.

PILESTIFF

```
100  PRINT "INITIAL STIFFNESS FOR STATIC CONDITIONS"
105  PRINT
110  INPUT "INPUT THETA (DEG) ":THETA
115  PRINT
120  INPUT "INPUT LENGTH TO LOAD (FT) ":LM
125  PRINT
130  INPUT "INPUT WGT OF LOAD (LBS) ":WL
135  PRINT
140  INPUT "INPUT PILE LENGTH (FT) ":LP
145  PRINT
150  INPUT "INPUT PILE WGT (LBS) ":WP
155  PRINT
160  INPUT "INPUT DEPTH TO HINGE ":D
165  PRINT
170  INPUT "INPUT PILE DIAM (FT) ":DP
175  PRINT
180  INPUT "INPUT WIND VEL (FT/S) ":UA
185  PRINT
190  INPUT "INPUT LENGTH TO BOARDS (FT) ":LB
195  PRINT
200  INPUT "INPUT AREA OF BOARDS (FT^2) ":AB
205  PRINT
210  INPUT "INPUT CUR VEL (FT/S) ":UC
215  PRINT
220 RA = .077 / 32.2
230 RW = 64.0 / 32.2
240 CA = 1.0
250 CW = 1.0
260 CB = 1.28
270 K1 = LM * WL + .5 * LP * WP + (.25 * RA * CA * DP * (LP ^ 2 - D ^
2) * (UA ^ 2) + .5 * RA * CB * AB * LB * (UA ^ 2) + .25 * (D ^ 2) * RW
 * CW * DP * (UC ^ 2)) / (THETA * 3.1416 / 180)
280  PRINT "INITIAL STIFFNESS K1 (FT-LBS/RAD) = ":K1
290  END
```

PILEFREQ

```
100  PRINT "PILE NATURAL FREQUENCY"
105  PRINT
110  INPUT "INPUT INIT STIFF K1 (FT-LBS/RAD) ":K1
115  PRINT
120  INPUT "INPUT LENGTH TO LOAD (FT) ":LM
125  PRINT
130  INPUT "INPUT WGT OF LOAD (LBS) ":WL
135  PRINT
140  INPUT "INPUT LENGTH OF PILE (FT) ":LP
145  PRINT
150  INPUT "INPUT WGT OF PILE (LBS) ":WP
155  PRINT
160  INPUT "INPUT DIAM OF PILE (FT) ":DP
165  PRINT
170  INPUT "INPUT DEPTH TO HINGE (FT) ":D
175  PRINT
180 RW = 64.0 / 32.2
190 CM = 2.0
200 MP = WP / 32.2
210 ML = WL / 32.2
220 IH = MP * (LP ^ 2) / 3 + (LM ^ 2) * ML + (3.1416 / 12) * RW * CM *
 (DP ^ 2) * (D ^ 3)
230 NF = ((K1 - LM * WL - .5 * LP * WP) / IH) ^ .5
240  PRINT "NATURAL FREQUENCY (RAD/S) = ":NF
245  PRINT
250  PRINT "NATURAL PERIOD (S) = ":2 * 3.1416 / NF
260  END
```

WAVELENGTH

```
10  PRINT "WAVELENGTH CALCULATION"
20  PRINT "FOR A REGULAR WAVE"
25  PRINT
30  INPUT "INPUT WAVE PERIOD (S) ":PER
35  PRINT
40  INPUT "INPUT DEPTH (FT) ":D
45  PRINT
50 PI = 3.1416
60 G = 32.2
70 E = .01
80 L0 = G * (PER ^ 2) / (2 * PI)
90 L = L0
100 F = (L / L0) - ( EXP (2 * PI * D / L) -  EXP ( - 2 * PI * D / L))
/ ( EXP (2 * PI * D / L) +  EXP ( - 2 * PI * D / L))
120  IF  ABS (F) < E THEN  GOTO 160
130 DF = (1 / L0) + (( EXP (2 * PI * D / L) +  EXP ( - 2 * PI * D / L)
) ^ ( - 2)) * 8 * PI * D / (L ^ 2)
140 L = L - F / DF
150  GOTO 100
160  PRINT "WAVELENGTH = ":L
```

```
1  PRINT "PILE MOTION FOR OPERATIONAL CONDITIONS"
5  PRINT
10  INPUT "INPUT STEPSIZE (S) ":H
15  PRINT
20  INPUT "INPUT MAX T (S) ":MAX
25  PRINT
30 L% =  INT (MAX / H)
40  INPUT "INPUT 1ST STIFFNESS CONSTANT K1 (FT-LBS/RAD) ":K1
45  PRINT
50  INPUT "INPUT 2ND STIFFNESS CONSTANT K2 (FT-LBS/RAD) ":K2
55  PRINT
60  INPUT "INPUT BREAKPOINT ANGLE (DEG) ":BA
61 BTHETA = BA * 3.1416 / 180
65  PRINT
70  INPUT "INPUT LOAD WGT (LBS) ":WL
75  PRINT
80 ML = WL / 32.2
90  INPUT "INPUT PILE WGT (LBS) ":WP
95  PRINT
100 MP = WP / 32.2
110  INPUT "INPUT PILE LENGTH (FT) ":LP
115  PRINT
120  INPUT "INPUT PILE DIAMETER (FT) ":DP
125  PRINT
130  INPUT "INPUT LENGTH TO LOAD (FT) ":LM
135  PRINT
140  INPUT "INPUT LENGTH TO BOARDS (FT) ":LB
145  PRINT
150  INPUT "INPUT DEPTH TO HINGE (FT) ":D
155  PRINT
160  INPUT "INPUT TOTAL DEPTH (FT) ":DT
165  PRINT
170  INPUT "INPUT WIND VEL (FT/S) ":UA
175  PRINT
180  INPUT "INPUT CUR VEL (FT/S) ":UC
185  PRINT
190  INPUT "INPUT WAVE HGT (FT) ":HW
195  PRINT
200  INPUT "INPUT WAVE PERIOD (S) ":PER
205  PRINT
210 SIGMA = 2 * 3.1416 / PER
220  INPUT "INPUT WAVE LENGTH (FT) ":LAMBDA
225  PRINT
230 KA = 2 * 3.1416 / LAMBDA
240 RA = .077 / 32.2
250 RW = 64.0 / 32.2
260 AB = 36
270 CA = 1.0
280 CW = 1.0
290 CB = 1.28
300 CM = 2.0
302 C1 = .5 * RW * CW * DP
304 C2 = .5 * HW * SIGMA / ( EXP (KA * DT) -  EXP ( - KA * DT))
306 C3 =  - (3.1416 / 8) * RW * CM * (DP ^ 2) * (SIGMA ^ 2) * HW / ( E
XP (KA * DT) -  EXP ( - KA * DT))
```

```
310 IH = (MP * LP ^ 2) / 3 + ML * LM ^ 2 + CM * RW * (3.1416 / 12) * (
DP ^ 2) * (D ^ 3)
320  DIM T(L% + 2.3)
330  DIM THETA(L% + 2.3)
340  DIM OMEGA(L% + 2.3)
350  DIM K(3)
360  DIM M(3)
370  DIM MH(3)
380  DIM MG(3)
390  DIM MW(3)
400  DIM MC(3)
410 I% = 0
420 T(0.0) = 0
430 THETA(0.0) = (.25 * (LP ^ 2 - D ^ 2) * RA * CA * DP * UA ^ 2 + .5
* LB * RA * CB * AB * UA ^ 2 + .25 * D * RW * CW * DP * D * UC ^ 2) /
(K1 - (LM * WL + .5 * LP * WP))
440  PRINT "STATIC EQUIL ANGLE = ";THETA(0.0) * 180 / 3.1416
445  PRINT
447  PRINT "TIME (S) = ";T(I%.0);"  THETA (DEG) = ";THETA(I%.0) * 180
/ 3.1416
450 T(I% + 1.0) = T(I%.0) + H
460  IF T(I% + 1.0) > MAX THEN  GOTO 785
470 T(I%.1) = T(I%.0) + .5 * H
480 T(I%.2) = T(I%.1)
490 T(I%.3) = T(I%.0) + H
500 J% = 0
510 K(J%) = OMEGA(I%.J%)
520  IF THETA(I%.J%) > (BTHETA) THEN  GOTO 560
530  IF THETA(I%.J%) + BTHETA < 0 THEN  GOTO 580
540 MH(J%) = K1 * THETA(I%.J%)
550  GOTO 590
560 MH(J%) = K1 * BTHETA + K2 * (THETA(I%.J%) - BTHETA)
570  GOTO 590
580 MH(J%) =  - K1 * BTHETA + K2 * (THETA(I%.J%) + BTHETA)
590 MG(J%) = (LM * WL + .5 * LP * WP) *  SIN (THETA(I%.J%))
600 MW(J%) = .25 * ((LP *  COS (THETA(I%.J%))) ^ 2 - D ^ 2) * RA * CA
* DP * UA ^ 2 + LB *  COS (THETA(I%.J%)) * .5 * RA * CB * AB * UA ^ 2
610  DEF  FN MD(Y) = (D + Y) * C1 * ((C2 * ( EXP (KA * DT + KA * Y) +
 EXP ( - KA * DT - KA * Y)) *  COS (SIGMA * T(I%.J%)) + UC - (D + Y) *
 OMEGA(I%.J%)) ^ 2) *  SGN (C2 * ( EXP (KA * DT + KA * Y) +  EXP ( - K
A * DT - KA * Y)) *  COS (SIGMA * T(I%.J%)) + UC - (D + Y) * OMEGA(I%.
J%))
612  DEF  FN MM(Y) = (D + Y) * C3 * ( EXP (KA * DT + KA * Y) +  EXP (
 - KA * DT - KA * Y)) *  SIN (SIGMA * T(I%.J%))
620 DLTA = D / 10
630 SUM = 0
640  FOR N = 1 TO 9
650 Y =  - D + (DLTA * N)
660 SUM = SUM +  FN MD(Y) +  FN MM(Y)
670  NEXT N
680 MC(J%) = DLTA * (SUM + .5 * ( FN MD( - D) +  FN MM( - D) +  FN MD(
0) +  FN MM(0)))
690 M(J%) = ( - MH(J%) + MG(J%) + MW(J%) + MC(J%)) / IH
700  IF J% = 3 THEN  GOTO 750
710 THETA(I%.J% + 1) = THETA(I%.0) + (T(I%.J% + 1) - T(I%.0)) * K(J%)
720 OMEGA(I%.J% + 1) = OMEGA(I%.0) + (T(I%.J% + 1) - T(I%.0)) * M(J%)
730 J% = J% + 1
740  GOTO 510
750 THETA(I% + 1.0) = THETA(I%.0) + (H / 6) * (K(0) + 2 * K(1) + 2 * K
(2) + K(3))
```

```
760 OMEGA(I% + 1.0) = OMEGA(I%.0) + (H / 6) * (M(0) + 2 * M(1) + 2 * M
(2) + M(3))
770 I% = I% + 1
775  PRINT "TIME (S) = ":T(I%.0):"  THETA (DEG) = ":THETA(I%.0) * 180
/ 3.1416
780  GOTO 450
785  PRINT
790  INPUT "INPUT INTERVAL (# OF TIME STEPS) FOR OUTPUT ":ITRVL
800  PR# 1
810 I% = 0
820  IF THETA(I%.0) > (BTHETA) THEN  GOTO 860
830  IF THETA(I%.0) + BTHETA < 0 THEN  GOTO 880
840 MH(0) = K1 * THETA(I%.0)
850  GOTO 890
860 MH(0) = K1 * BTHETA + K2 * (THETA(I%.0) - BTHETA)
870  GOTO 890
880 MH(0) =  - K1 * BTHETA + K2 * (THETA(I%.0) + BTHETA)
890  PRINT "T (S) = ":T(I%.0):" THETA (DEG) = ":THETA(I%.0) * 180 / 3.
1416:"  HINGE MOMENT (FT-LBS) = ":MH(0)
895  PRINT
900 I% = I% + ITRVL
910  IF I% > L% THEN  GOTO 930
920  GOTO 820
930  PR# 0
940  END
```

```
1  PRINT "PILE MOTION FOR HURRICANE CONDITIONS"
5  PRINT
10  INPUT "INPUT STEPSIZE (S) ":H
15  PRINT
20  INPUT "INPUT MAX T (S) ":MAX
25  PRINT
30 L% =  INT (MAX / H)
40  INPUT "INPUT 1ST STIFFNESS CONSTANT K1 (FT-LBS/RAD) ":K1
45  PRINT
50  INPUT "INPUT 2ND STIFFNESS CONSTANT K2 (FT-LBS/RAD) ":K2
55  PRINT
60  INPUT "INPUT BREAKPOINT ANGLE (DEG) ":BA
61 BTHETA = BA * 3.1416 / 180
65  PRINT
70  INPUT "INPUT LOAD WGT (LBS) ":WL
75  PRINT
80 ML = WL / 32.2
90  INPUT "INPUT PILE WGT (LBS) ":WP
95  PRINT
100 MP = WP / 32.2
110  INPUT "INPUT PILE LENGTH (FT) ":LP
115  PRINT
120  INPUT "INPUT PILE DIAMETER (FT) ":DP
125  PRINT
130  INPUT "INPUT LENGTH TO LOAD (FT) ":LM
135  PRINT
150  INPUT "INPUT DEPTH TO HINGE (FT) ":D
155  PRINT
160  INPUT "INPUT TOTAL DEPTH (FT) ":DT
165  PRINT
170  INPUT "INPUT WIND VEL (FT/S) ":UA
175  PRINT
180  INPUT "INPUT CUR VEL (FT/S) ":UC
185  PRINT
190  INPUT "INPUT WAVE HGT (FT) ":HW
195  PRINT
200  INPUT "INPUT WAVE PERIOD (S) ":PER
205  PRINT
210 SIGMA = 2 * 3.1416 / PER
220  INPUT "INPUT WAVE LENGTH (FT) ":LAMBDA
225  PRINT
230 KA = 2 * 3.1416 / LAMBDA
240 RA = .077 / 32.2
250 RW = 64.0 / 32.2
260 AB = 36
270 CA = 1.0
280 CW = 1.0
300 CM = 2.0
310 IM = (MP * LP ^ 2) / 3 + ML * LM ^ 2
320  DIM T(L% + 2,3)
330  DIM THETA(L% + 2,3)
340  DIM OMEGA(L% + 2,3)
350  DIM K(3)
360  DIM M(3)
370  DIM MH(3)
```

```
380  DIM MG(3)
390  DIM MW(3)
400  DIM MC(3)
410 I% = 0
420 T(0.0) = 0
430 THETA(0.0) = (.25 * (LP ^ 2 - D ^ 2) * RA * CA * DP * UA ^ 2 + .5
* LB * RA * CB * AB * UA ^ 2 + .25 * D * RW * CW * DP * D * UC ^ 2) /
(K1 - (LM * WL + .5 * LP * WP))
440  PRINT "STATIC EQUIL ANGLE = ":THETA(0.0) * 180 / 3.1416
445  PRINT
447  PRINT "TIME (S) = ":T(I%.0):"  THETA (DEG) = ":THETA(I%.0) * 180
/ 3.1416
450 T(I% + 1.0) = T(I%.0) + H
460  IF T(I% + 1.0) > MAX THEN  GOTO 785
470 T(I%.1) = T(I%.0) + .5 * H
480 T(I%.2) = T(I%.1)
490 T(I%.3) = T(I%.0) + H
500 J% = 0
510 X(J%) = OMEGA(I%.J%)
520  IF THETA(I%.J%) > (BTHETA) THEN  GOTO 560
530  IF THETA(I%.J%) + BTHETA < 0 THEN  GOTO 580
540 MH(J%) = K1 * THETA(I%.J%)
550  GOTO 590
560 MH(J%) = K1 * BTHETA + K2 * (THETA(I%.J%) - BTHETA)
570  GOTO 590
580 MH(J%) =  - K1 * BTHETA + K2 * (THETA(I%.J%) + BTHETA)
590 MG(J%) = (LM * WL + .5 * LP * WP) *  SIN (THETA(I%.J%))
600  IF LP *  COS (THETA(I%.J%)) < D THEN  GOTO 606
602 MW(J%) = .25 * ((LP *  COS (THETA(I%.J%))) ^ 2 - D ^ 2) * RA * CA
* DP * (UA ^ 2)
603 LS = D /  COS (THETA(I%.J%))
604  GOTO 608
606 MW(J%) = 0
607 LS = LP
608 IH = IM + (3.1416 / 12) * (DP ^ 2) * RW * CM * (LS ^ 3)
610 DLTA = LS / 10
615 SUM = 0
620  FOR N = 1 TO 10
625 S = DLTA * N
630 X = S *  SIN (THETA(I%.J%))
635 Y =  - D + S *  COS (THETA(I%.J%))
640 U = .5 * SIGMA * HW * (( EXP (KA * DT + KA * Y) +  EXP ( - KA * DT
 - KA * Y)) / ( EXP (KA * DT) -  EXP ( - KA * DT))) *  COS (KA * X - S
IGMA * T(I%.J%))
645 V = .5 * SIGMA * HW * (( EXP (KA * DT + KA * Y) -  EXP ( - KA * DT
 - KA * Y)) / ( EXP (KA * DT) -  EXP ( - KA * DT))) *  SIN (KA * X - S
IGMA * T(I%.J%))
650 UDOT = .5 * (SIGMA ^ 2) * HW * (( EXP (KA * DT + KA * Y) +  EXP (
- KA * DT - KA * Y)) / ( EXP (KA * DT) -  EXP ( - KA * DT))) *  SIN (K
A * X - SIGMA * T(I%.J%))
655 VDOT =  - .5 * (SIGMA ^ 2) * HW * (( EXP (KA * DT + KA * Y) -  EXP
 ( - KA * DT - KA * Y)) / ( EXP (KA * DT) -  EXP ( - KA * DT))) *  COS
 (KA * X - SIGMA * T(I%.J%))
660 FD = .5 * RW * CW * DP * ((U *  COS (THETA(I%.J%)) - V *  SIN (THE
TA(I%.J%)) + UC *  COS (THETA(I%.J%)) - S * OMEGA(I%.J%)) ^ 2) *  SGN
(U *  COS (THETA(I%.J%)) - V *  SIN (THETA(I%.J%)) + UC *  COS (THETA(
I%.J%)) - S * OMEGA(I%.J%))
662 FI = .25 * 3.1416 * RW * CM * (DP ^ 2) * (UDOT *  COS (THETA(I%.J%
)) - VDOT *  SIN (THETA(I%.J%)) - UC * ( SIN (THETA(I%.J%))) * OMEGA(I
%.J%))
```

```
664  IF N > 9.9 THEN  GOTO 668
666 SUM = SUM + S * (FD + FI)
667  GOTO 670
668 SUM = SUM + .5 * S * (FD + FI)
670  NEXT N
680 MC(J%) = DLTA * SUM
690 M(J%) = ( - MH(J%) + MG(J%) + MW(J%) + MC(J%)) / IH
700  IF J% = 3 THEN  GOTO 750
710 THETA(I%,J% + 1) = THETA(I%,0) + (T(I%,J% + 1) - T(I%,0)) * K(J%)
720 OMEGA(I%,J% + 1) = OMEGA(I%,0) + (T(I%,J% + 1) - T(I%,0)) * M(J%)
730 J% = J% + 1
740  GOTO 510
750 THETA(I% + 1,0) = THETA(I%,0) + (H / 6) * (K(0) + 2 * K(1) + 2 * K
(2) + K(3))
760 OMEGA(I% + 1,0) = OMEGA(I%,0) + (H / 6) * (M(0) + 2 * M(1) + 2 * M
(2) + M(3))
770 I% = I% + 1
775  PRINT "TIME (S) = ";T(I%,0);"  THETA (DEG) = ";THETA(I%,0) * 180
/ 3.1416
780  GOTO 450
785  PRINT
790  INPUT "INPUT INTERVAL (# OF TIME STEPS) FOR OUTPUT ";ITRVL
800  PR# 1
810 I% = 0
820  IF THETA(I%,0) > (BTHETA) THEN  GOTO 860
830  IF THETA(I%,0) + BTHETA < 0 THEN  GOTO 880
840 MH(0) = K1 * THETA(I%,0)
850  GOTO 890
860 MH(0) = K1 * BTHETA + K2 * (THETA(I%,0) - BTHETA)
870  GOTO 890
880 MH(0) =  - K1 * BTHETA + K2 * (THETA(I%,0) + BTHETA)
890  PRINT "T (S) = ";T(I%,0);"  THETA (DEG) = ";THETA(I%,0) * 180 / 3
.1416;"  HINGE MOMENT (FT-LBS) = ";MH(0)
895  PRINT
900 I% = I% + ITRVL
910  IF I% > L% THEN  GOTO 930
920  GOTO 820
930  PR# 0
940  END
```

COLPILE

```
1  PRINT "PILE DYNAMICS DURING COLLISION"
5  PRINT
10  INPUT "INPUT STEPSIZE (S) ":H
15  PRINT
20  INPUT "INPUT 1ST STIFFNESS CONSTANT K1 (FT-LBS/RAD) ":K1
25  PRINT
30  INPUT "INPUT 2ND STIFFNESS CONSTANT K2 (FT-LBS/RAD) ":K2
35  PRINT
40  INPUT "INPUT BREAKPOINT ANGLE (DEG) ":BA
45  PRINT
50  INPUT "INPUT LOAD WEIGHT (LBS) ":WL
55  PRINT
60  INPUT "INPUT PILE WEIGHT (LBS) ":WP
65  PRINT
70  INPUT "INPUT PILE LENGTH (FT) ":LP
75  PRINT
80  INPUT "INPUT PILE DIAMETER (FT) ":DP
85  PRINT
90  INPUT "INPUT LENGTH TO LOAD (FT) ":LM
95  PRINT
100  INPUT "INPUT DEPTH TO HINGE (FT) ":D
105  PRINT
110  INPUT "INPUT TOTAL DEPTH (FT) ":DT
115  PRINT
120  INPUT "INPUT CURRENT VELOCITY (FT/S) ":UC
122  PRINT
125  INPUT "INPUT BARGE COEFFICIENT OF FRICTION ":MU
127  PRINT
130  INPUT "INPUT BARGE FREEBOARD (FT) ":FB
135  PRINT
140  INPUT "INPUT BARGE DRAFT (FT) ":DB
145  PRINT
150  INPUT "INPUT BARGE BOW ANGLE (DEG) ":FA
155  PRINT
160  INPUT "INPUT BARGE LENGTH (FT) ":LB
165  PRINT
170  INPUT "INPUT BARGE SPEED (FT/S) ":UB
175  PRINT
180 CW = 1.0
185 RW = 64.0 / 32.2
190 CM = 2.0
195 PI = 3.1416
200 BTHETA = BA * PI / 180
210 FTHETA = FA * PI / 180
220 LF = (DB + FB) *  TAN (FTHETA)
225 PHI =  ATN (MU)
230 LK = LB - LF
240 HB = D - DB
250 TF = ((D + FB) / UB) *  TAN (FTHETA)
260 TNKT =  SQR ((LP ^ 2 / HB ^ 2) - 1)
270 KTHETA =  ATN (TNKT)
280 TX = (HB * TNKT + LF) / UB
290 TR = TX + LK / UB
300 ML = WL / 32.2
310 MP = WP / 32.2
```

```
320 IM = (MP * LP ^ 2) / 3 + ML * LM ^ 2
330 T = 0
335  PR# 1
340  PRINT "IMPACT AT TOP OF BARGE BOW"
350  PRINT "TIME (S) = 0  THETA (DEG) = 0 "
355 IH = IM + RW * CM * PI * (DP ^ 2) * (D ^ 3) / 12
360 MDT = IH * UB / (D + FB)
370 FDT = (IH * UB) / ((D + FB) ^ 2)
375 MA = CM * RW * PI * (DP ^ 2) * D / 4
380 HDT = (IH / (D + FB) - (ML * LM + .5 * (MP * LP + MA * D))) * UB /
 (D + FB)
390 VDT = 0
400  PRINT "BARGE MOMENT IMPULSE (FT-LB-S) = ";MDT;"  BARGE FORCE IMPU
LSE (LB-S) = ";FDT
410  PRINT "HORZ REACT IMPULSE (LB-S) = ";HDT;"  VERT REACT IMPULSE (L
B-S) = ";VDT
415  PRINT
418  IF (T + H) >  = TF THEN  GOTO 590
420 T = T + H
430 THETA =  ATN (UB * T / (D + FB))
431  IF (D + FB) /  COS (THETA) <  = LP THEN  GOTO 440
432 THETA =  ATN ((1 - (D + FB) / (LP *  COS (THETA))) *  TAN (FTHETA)
 + UB * T / (LP *  COS (THETA)))
433 OMEGA = UB / (LP * ( COS (THETA) +  TAN (FTHETA) *  SIN (THETA)))
434 ALPHA = ( SIN (THETA) -  TAN (FTHETA) *  COS (THETA)) * ((UB / LP)
 ^ 2) / (( COS (THETA) +  TAN (FTHETA) *  SIN (THETA)) ^ 3)
435 LC = LP
436  GOTO 460
440 OMEGA = UB * (( COS (THETA)) ^ 2) / (D + FB)
450 ALPHA =  - 2 * ((UB / (D + FB)) ^ 2) * (( COS (THETA)) ^ 3) *  SIN
 (THETA)
455 LC = (D + FB) /  COS (THETA)
460  PRINT "TIME (S) = ";T;"  THETA (DEG) = ";THETA * 180 / PI
468  IF LP *  COS (THETA) < D THEN  GOTO 474
470 LS = D /  COS (THETA)
472  GOTO 480
474 LS = LP
480 IH = IM + RW * CM * PI * (DP ^ 2) * (LS ^ 3) / 12
485 MA = CM * RW * PI * (DP ^ 2) * LS / 4
490  GOSUB 2000
500  GOSUB 3000
510 M = IH * ALPHA + MH - LM * WL *  SIN (THETA) - .5 * LP * WP *  SIN
 (THETA) - MC
515  GOSUB 4000
520  IF (D + FB) /  COS (THETA) > LP THEN  GOTO 552
530 F = M / (LC *  COS (PHI))
540 RH = F *  COS (THETA - PHI) + FC *  COS (THETA) + (ML * LM + .5 *
MP * LP) * ((OMEGA ^ 2) *  SIN (THETA) - ALPHA *  COS (THETA)) - MA *
.5 * LS * ALPHA *  COS (THETA)
550 RV = F *  SIN (THETA - PHI) + FC *  SIN (THETA) + WL + WP - (ML *
LM + .5 * MP * LP) * (ALPHA *  SIN (THETA) + (OMEGA ^ 2) *  COS (THETA
)) - MA * .5 * LS * ALPHA *  SIN (THETA)
551  GOTO 560
552 F = M / (LP *  COS (THETA - FTHETA + PHI))
553 RH = F *  COS (FTHETA - PHI) + FC *  COS (THETA) + (ML * LM + .5 *
 MP * LP) * ((OMEGA ^ 2) *  SIN (THETA) - ALPHA *  COS (THETA)) - MA *
 .5 * LS * ALPHA *  COS (THETA)
554 RV = F *  SIN (FTHETA - PHI) + FC *  SIN (THETA) + WL + WP - (ML *
 LM + .5 * MP * LP) * (ALPHA *  SIN (THETA) + (OMEGA ^ 2) *  COS (THET
A)) - MA * .5 * LS * ALPHA *  SIN (THETA)
```

```
560  PRINT "BARGE MOMENT (FT-LBS) = ":M:"  BARGE FORCE (LBS) = ":F
570  PRINT "HINGE MOMENT (FT-LBS) = ":MH:"  HORZ REACT (LBS) = ":RH:"
 VERT REACT (LBS) = ":RV
575  PRINT
580  GOTO 418
590  PRINT "IMPACT AT BOTTOM OF BARGE BOW"
600  PRINT "TIME (S) = ":TF:"  THETA (DEG) = ":FTHETA * 180 / PI
602  IF LP *  COS (FTHETA) < D THEN  GOTO 605
603 LS = D /  COS (FTHETA)
604  GOTO 606
605 LS = LP
606 IH = IM + RW * CM * PI * (DP ^ 2) * (LS ^ 3) / 12
608 MA = CM * RW * PI * (DP ^ 2) * LS / 4
610 LC = HB /  COS (FTHETA)
620 MDT = IH * UB * (( COS (FTHETA)) ^ 2) * (1 / HB - (1 / (D + FB)))
630 FDT = MDT / LC
640 RDT = (IH / LC - (ML * LM + .5 * (MP * LP + MA * LS))) * UB * (( C
OS (FTHETA)) ^ 2) * ((1 / HB) - (1 / (D + FB)))
650 HDT = RDT *  COS (FTHETA)
660 VDT = RDT *  SIN (FTHETA)
670  PRINT "BARGE MOMENT IMPULSE (FT-LB-S) = ":MDT:"  BARGE FORCE IMP
ULSE (LB-S) = ":FDT
680  PRINT "HORZ REACT IMPULSE (LB-S) = ":HDT:"VERT REACT IMPULSE (LB-
S) = ":VDT
685  PRINT
688  IF (T + H) >  = TK THEN  GOTO 910
700 T = T + H
710 THETA =  ATN ((UB * T - LF) / HB)
720 OMEGA = (UB / HB) * (( COS (THETA)) ^ 2)
730 ALPHA =  - 2 * ((UB / HB) ^ 2) * (( COS (THETA)) ^ 3) *  SIN (THET
A)
740 LC = HB /  COS (THETA)
750  IF LP *  COS (THETA) < D THEN  GOTO 780
760 LS = D /  COS (THETA)
770  GOTO 790
780 LS = LP
790 IH = IM + RW * CM * PI * (DP ^ 2) * (LS ^ 3) / 12
795 MA = CM * RW * PI * (DP ^ 2) * LS / 4
800  PRINT "TIME (S) = ":T:"  THETA (DEG) = ":THETA * 180 / PI
810  GOSUB 2000
820  GOSUB 3000
830 M = IH * ALPHA + MH - LM * WL *  SIN (THETA) - .5 * LP * WP *  SIN
 (THETA) - MC
840 F = M / (LC *  COS (PHI))
850  GOSUB 4000
860 RH = F *  COS (THETA - PHI) + FC *  COS (THETA) + (ML * LM + .5 *
MP * LP) * ((OMEGA ^ 2) *  SIN (THETA) - ALPHA *  COS (THETA)) - MA *
.5 * LS * ALPHA *  COS (THETA)
870 RV = F *  SIN (THETA - PHI) + FC *  SIN (THETA) + WL + WP - (ML *
LM + .5 * MP * LP) * (ALPHA *  SIN (THETA) + (OMEGA ^ 2) *  COS (THETA
)) - MA * .5 * LS * ALPHA *  SIN (THETA)
880  PRINT "BARGE MOMENT (FT-LBS)= ":M:"  BARGE FORCE (LBS)= ":F
890  PRINT "HINGE MOMENT (FT-LBS)= ":MH:"  HORZ REACT (LBS)= ":RH:"  V
ERT REACT (LBS) = ":RV
895  PRINT
900  GOTO 688
910  PRINT "PILE IN CONTACT WITH BARGE BOTTOM"
920  PRINT "TIME DURATION (S) IS FROM ":TK:" TO ":TR:
925  PRINT "THETA (DEG) = ":KTHETA * 180 / PI
930 THETA = KTHETA
```

```
940 OMEGA = 0
950 ALPHA = 0
960 LC = LP
970 LS = LP
980  GOSUB 2000
990  GOSUB 3000
1000 M = MH - LM * WL *  SIN (THETA) - .5 * LP * WP *  SIN (THETA) - M
C
1010 F = M / (LP *  SIN (KTHETA + PHI))
1020  GOSUB 4000
1030 RH = F *  SIN (PHI) + FC *  COS (THETA)
1040 RV = F *  COS (PHI) + FC *  SIN (THETA) + WL + WP
1050  PRINT "BARGE MOMENT (FT-LBS) = ":M:"  BARGE FORCE (LBS)= ":F
1060  PRINT "HINGE MOMENT (FT-LBS) = ":MH:"  HORZ REACT (LBS) = ":RH:"
 VERT REACT (LBS) = ":RV
1070  PRINT "PILE RECOVERY IS INITIATED AT T (S) = ":TR
1080  PR# 0
1090  END
2000  IF THETA > (BTHETA) THEN  GOTO 2040
2010  IF THETA < ( - BTHETA) THEN  GOTO 2060
2020 MH = K1 * THETA
2030  GOTO 2070
2040 MH = K1 * BTHETA + K2 * (THETA - BTHETA)
2050  GOTO 2070
2060 MH =  - K1 * BTHETA + K2 * (THETA + BTHETA)
2070  RETURN
3000 DLTA = LS / 10
3010 SUM = 0
3020  FOR N = 1 TO 10
3030 S = DLTA * N
3040 FD = .5 * RW * CW * DP * ((UC *  COS (THETA) - S * OMEGA) ^ 2) *
 SGN (UC *  COS (THETA) - S * OMEGA)
3050 FI =  - .25 * PI * RW * CM * (DP ^ 2) * UC * OMEGA *  SIN (THETA)

3060  IF N > 9.9 THEN  GOTO 3090
3070 SUM = SUM + S * (FD + FI)
3080  GOTO 3100
3090 SUM = SUM + .5 * S * (FD + FI)
3100  NEXT N
3110 MC = DLTA * SUM
3120  RETURN
4000 DLTA = LS / 10
4010 SUM = 0
4020  FOR N = 0 TO 10
4030 S = DLTA * N
4040 FD = .5 * RW * CW * DP * ((UC *  COS (THETA) - S * OMEGA) ^ 2) *
 SGN (UC *  COS (THETA) - S * OMEGA)
4050 FI =  - .25 * PI * RW * CM * (DP ^ 2) * UC * OMEGA *  SIN (THETA)

4060  IF N < .9 THEN  GOTO 4100
4070  IF N > 9.9 THEN  GOTO 4100
4080 SUM = SUM + .5 * (FD + FI)
4090  GOTO 4110
4100 SUM = SUM + .5 * (FD + FI)
4110  NEXT N
4120 FC = DLTA * SUM
4130  RETURN
```

RECPILE

```
1  PRINT "PILE MOTION DURING RECOVERY"
5  PRINT
10  INPUT "INPUT STEPSIZE (S) ":H
15  PRINT
20  INPUT "INPUT MAX T (S) ":MAX
25  PRINT
30 L% =  INT (MAX / H)
40  INPUT "INPUT 1ST STIFFNESS CONSTANT K1 (FT-LBS/RAD) ":K1
45  PRINT
50  INPUT "INPUT 2ND STIFFNESS CONSTANT K2 (FT-LBS/RAD) ":K2
55  PRINT
60  INPUT "INPUT BREAKPOINT ANGLE (DEG) ":BA
61 BTHETA = BA * 3.1416 / 180
65  PRINT
70  INPUT "INPUT LOAD WGT (LBS) ":WL
75  PRINT
80 ML = WL / 32.2
90  INPUT "INPUT PILE WGT (LBS) ":WP
95  PRINT
100 MP = WP / 32.2
110  INPUT "INPUT PILE LENGTH (FT) ":LP
115  PRINT
120  INPUT "INPUT PILE DIAMETER (FT) ":DP
125  PRINT
130  INPUT "INPUT LENGTH TO LOAD (FT) ":LM
135  PRINT
150  INPUT "INPUT DEPTH TO HINGE (FT) ":D
155  PRINT
160  INPUT "INPUT TOTAL DEPTH (FT) ":DT
165  PRINT
180  INPUT "INPUT CUR VEL (FT/S) ":UC
185  PRINT
190  INPUT "INPUT INITIAL THETA (DEG) ":T0
195  PRINT
200 KTHETA = T0 * 3.1416 / 180
250 RW = 64.0 / 32.2
280 CW = 1.0
300 CM = 2.0
310 IM = (MP * LP ^ 2) / 3 + ML * LM ^ 2
320  DIM T(L% + 2.3)
330  DIM THETA(L% + 2.3)
340  DIM OMEGA(L% + 2.3)
350  DIM K(3)
360  DIM M(3)
370  DIM MH(3)
380  DIM MG(3)
400  DIM MC(3)
410 I% = 0
420 T(0.0) = 0
430 THETA(0.0) = KTHETA
447  PRINT "TIME (S) = ":T(I%.0):"  THETA (DEG) = ":THETA(I%.0) * 180
 / 3.1416
450 T(I% + 1.0) = T(I%.0) + H
460  IF T(I% + 1.0) > MAX THEN  GOTO 785
470 T(I%.1) = T(I%.0) + .5 * H
```

```
480 T(I%.2) = T(I%.1)
490 T(I%.3) = T(I%.0) + H
500 J% = 0
510 K(J%) = OMEGA(I%.J%)
520  IF THETA(I%.J%) ) (BTHETA) THEN  GOTO 560
530  IF THETA(I%.J%) + BTHETA ( 0 THEN  GOTO 580
540 MH(J%) = K1 * THETA(I%.J%)
550  GOTO 590
560 MH(J%) = K1 * BTHETA + K2 * (THETA(I%.J%) - BTHETA)
570  GOTO 590
580 MH(J%) =  - K1 * BTHETA + K2 * (THETA(I%.J%) + BTHETA)
590 MG(J%) = (LM * WL + .5 * LP * WP) *  SIN (THETA(I%.J%))
600  IF LP *  COS (THETA(I%.J%)) ( D THEN  GOTO 606
603 LS = D /  COS (THETA(I%.J%))
604  GOTO 608
606 LS = LP
608 IH = IM + (3.1416 / 12) * (DP ^ 2) * RW * CM * (LS ^ 3)
610 DLTA = LS / 10
615 SUM = 0
620  FOR N = 1 TO 10
625 S = DLTA * N
660 FD = .5 * RW * CW * DP * ((UC *  COS (THETA(I%.J%)) - S * OMEGA(I%
.J%)) ^ 2) *  SGN (UC *  COS (THETA(I%.J%)) - S * OMEGA(I%.J%))
662 FI =  - .25 * 3.1416 * RW * CM * (DP ^ 2) * UC * OMEGA(I%.J%) *  S
IN (THETA(I%.J%))
664  IF N ) 9.9 THEN  GOTO 668
666 SUM = SUM + S * (FD + FI)
667  GOTO 670
668 SUM = SUM + .5 * S * (FD + FI)
670  NEXT N
680 MC(J%) = DLTA * SUM
690 M(J%) = ( - MH(J%) + MG(J%) + MC(J%)) / IH
700  IF J% = 3 THEN  GOTO 750
710 THETA(I%.J% + 1) = THETA(I%.0) + (T(I%.J% + 1) - T(I%.0)) * K(J%)
720 OMEGA(I%.J% + 1) = OMEGA(I%.0) + (T(I%.J% + 1) - T(I%.0)) * M(J%)
730 J% = J% + 1
740  GOTO 510
750 THETA(I% + 1.0) = THETA(I%.0) + (H / 6) * (K(0) + 2 * K(1) + 2 * K
(2) + K(3))
760 OMEGA(I% + 1.0) = OMEGA(I%.0) + (H / 6) * (M(0) + 2 * M(1) + 2 * M
(2) + M(3))
770 I% = I% + 1
775  PRINT "TIME (S) = ":T(I%.0):"  THETA (DEG) = ":THETA(I%.0) * 180
/ 3.1416
780  GOTO 450
785  PRINT
790  INPUT "INPUT INTERVAL (# OF TIME STEPS) FOR OUTPUT ":ITRVL
800  PR# 1
810 I% = 0
820  IF THETA(I%.0) ) (BTHETA) THEN  GOTO 860
830  IF THETA(I%.0) + BTHETA ( 0 THEN  GOTO 880
840 MH(0) = K1 * THETA(I%.0)
850  GOTO 890
860 MH(0) = K1 * BTHETA + K2 * (THETA(I%.0) - BTHETA)
870  GOTO 890
880 MH(0) =  - K1 * BTHETA + K2 * (THETA(I%.0) + BTHETA)
890  PRINT "T (S) = ":T(I%.0):"  THETA (DEG) = ":THETA(I%.0) * 180 / 3
.1416:"  HINGE MOMENT (FT-LBS) = ":MH(0)
895  PRINT
900 I% = I% + ITRVL
```

```
910  IF I% > L% THEN  GOTO 930
920  GOTO 820
930  PR# 0
940  END
```

XIII. APPENDIX B: OTHER HINGE CONCEPTS

The rubber tube analysis results indicated that it would be necessary to consider hinge components which make use of springs. Many spring loaded mechanisms were investigated but not adopted. Several of the concepts which warranted serious consideration are presented in this appendix. In each case, the reason for their ultimate rejection is discussed.

A very simple concept using a central spring and a circular base is shown in Fig. 31. The spring is housed in the hollow pile, and the lower part of the pile is widened for increased stability. When tipped, the pile rocks on the base contact point, and spring tension provides the restoring moment. The spring is prestressed so the restoring moment develops at very small angle changes. While promising, this particular concept was rejected because there is no simple way to ensure that base contact is maintained during lower bow rake collision impact.

Peripheral stay/point universal joint concepts were then developed to provide a fixed point of attachment as well as obtain initial stiffness by means of prestressing. As shown in Fig. 32, the pile is centrally supported using a crossed axis universal joint, and its angular motion is restrained by stays placed on the periphery. The arrangement is such that if there is an angular change from the vertical, the stay on the outside of the bend immediately sustains the entire prestressing force. Thus a large restoring moment is generated at very small angles. This concept was not used in the manner shown in Fig. 32 because the joint requires 90 deg of rotation which is beyond the range of the standard, commercially available U-joint. In addition, the stay moment arm with respect to the joint decreases at large angles. Consequently the restoring moment is reduced below that required to return the pile to the upright position from a full knockdown.

The segmented pile/internal stay hinge system shown in Fig. 33 provides full articulation. Stay moment arm with respect to the hinge axes, however, is further

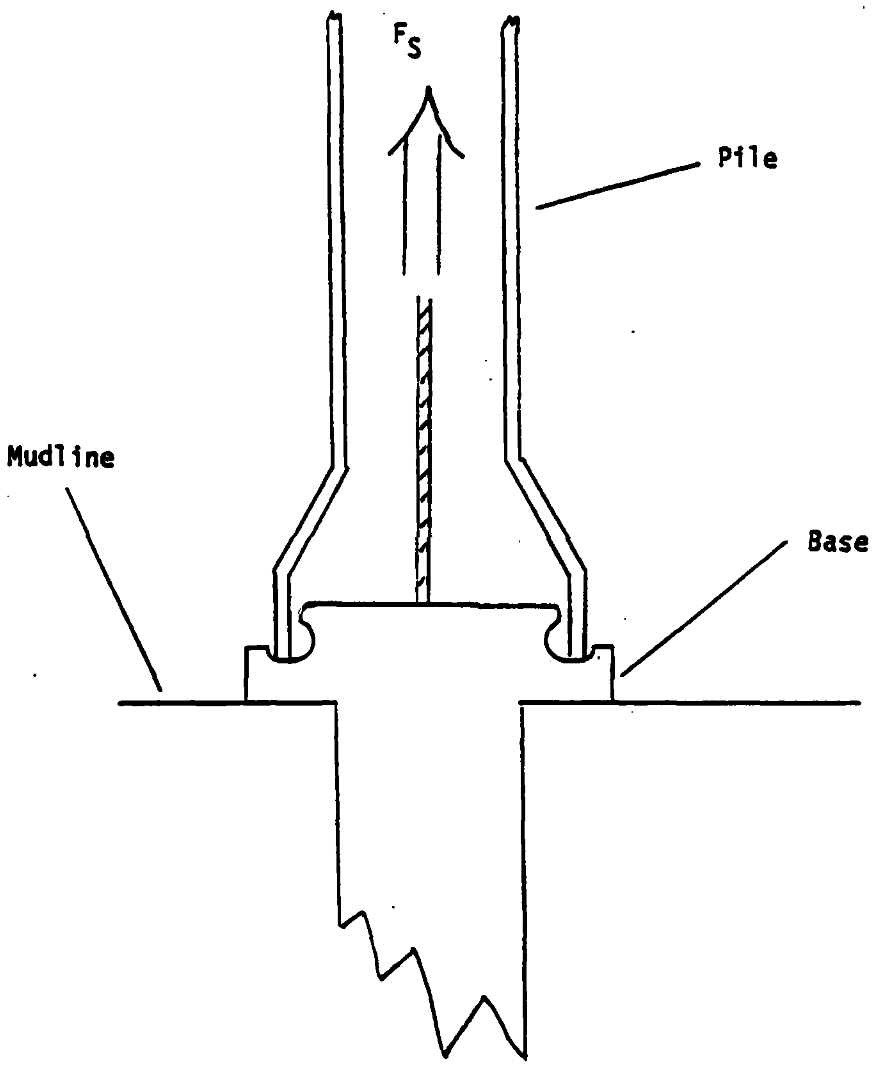

Fig. 31. Central spring/circular base hinge concept. F_S is the force due to a central, internal "spring" which is attached to the base (circular in plan view) by the cable shown.

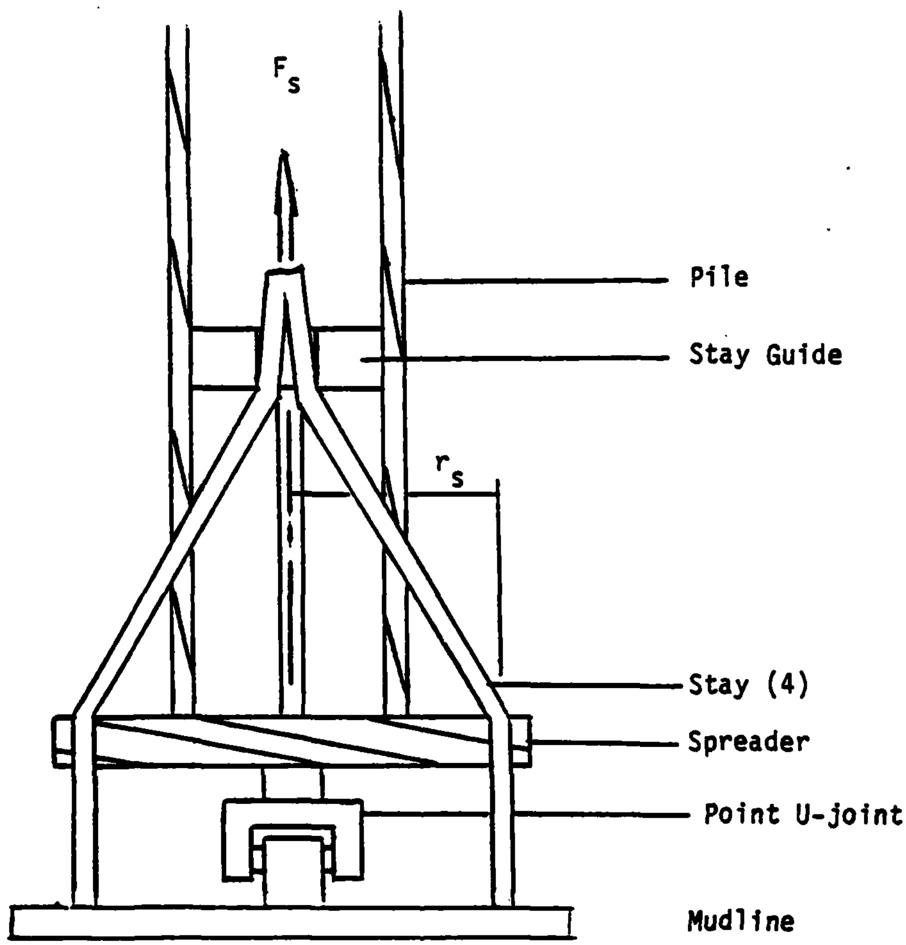

Fig. 32. The peripheral stay /point universal joint concept. Four stays are used which are prestressed by F_s according to Eq. 12.

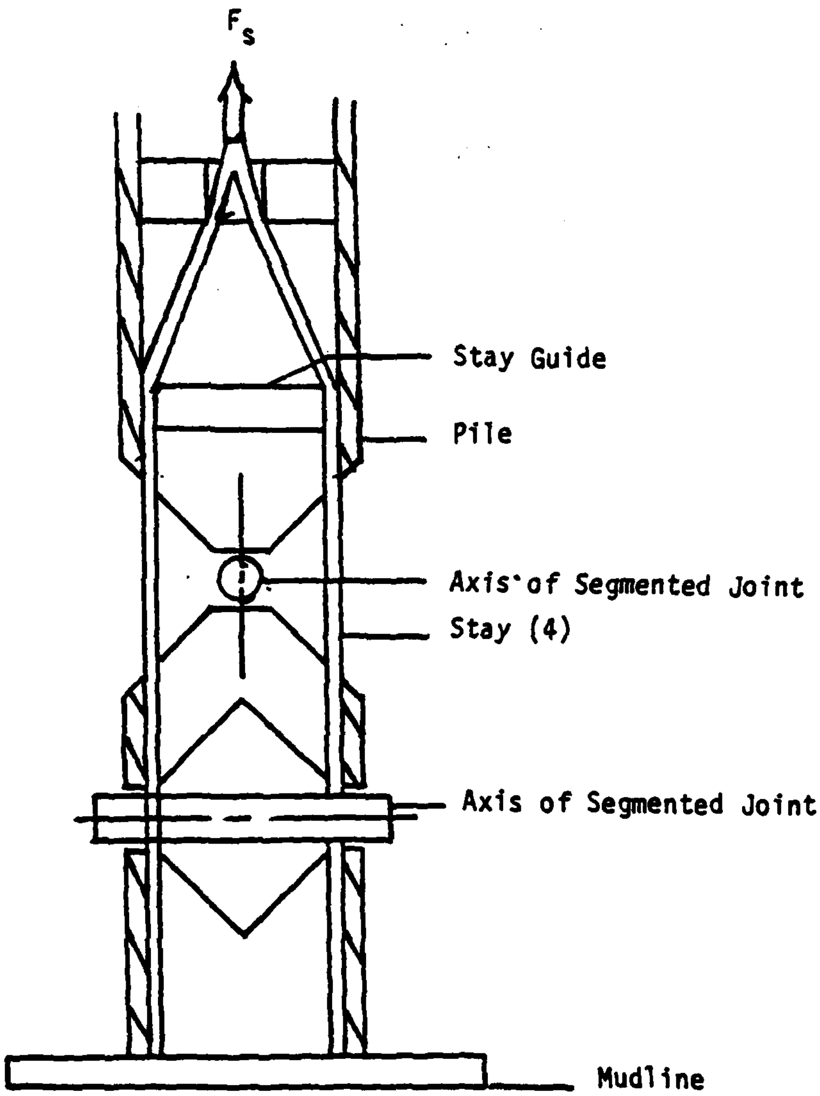

Fig. 33. The segmented pile/internal stay concept. Four internal stays are guided to lead across the joint notches. The stays are prestressed by F_s.

reduced. The concept was, therefore, rejected due to inadequate restoring moment stiffness.

The last concept presented here involves the use of a break-away shear pin. The spring in any of the previously described systems is replaced by a tension member. This member is prestressed and pinned at the top as shown in Fig. 34. When the pile is struck, the pin will fail in shear and the pile rotates freely at the hinge. The pile system remains connected enabling its position to be easily relocated. The system can then be reassembled without the use of a pile driver equipped barge. Though simple and workable, this system does not provide an automatic return to the operating position. Because assistance is required, this concept was judged not able to meet the fundamental design objective.

While the hinge concepts described in this appendix were not used, they were not without merit. In fact the final hinge concept adopted, as shown in Fig. 5, evolved from these earlier efforts and incorporates several of their more useful features.

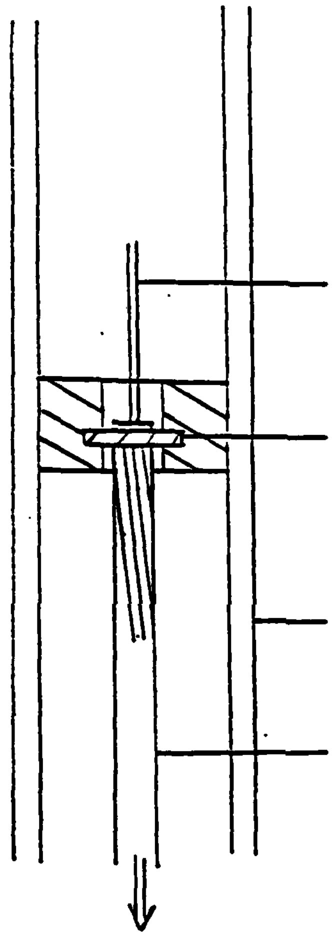

Fig. 34. The breakaway shear pin concept.

XIV. APPENDIX C: SPRING OPTIONS

Two principal concepts for creating the "spring" force F_s are possible - an airbag/cylinder concept and an elastic member such as a rubber band or an array of nylon ropes. It was found that helical steel springs are not suitable. Helical springs which possess the required stiffness and elastic range are much too large to fit inside the pile.

In the airbag concept, shown in Fig. 35, the bag is contained between a platform fixed to the inside of the pile wall and a moveable piston. The piston rod lies along the pile centerline and passes through the platform to a point where the stays are attached. The airbag is filled from the surface to a pressure corresponding to the necessary prestress force F_s. When the pile moves from the vertical, the air is further compressed contributing to a positive k_2 value. The bag operating pressure is in the vicinity of 400 psi which allows easy inflation. Conversations with engineers familiar with commercially available airbags, however, suggest that this arrangement pushes the limit of current technology.

The other acceptable spring concept involves the use of an elastic member. The stays are connected to one end of the member, and the member is then stretched until the load equals F_s. A worm gear jack arrangement, as illustrated in Fig. 36, could be used to accomplish the prestressing. The load-deflection characteristics of the member will be measured before installation so that the amount of elongation required to produce the desired F_s is known. The length increase at F_s should not be the maximum elongation so the member can stretch further during collision without exceeding the elastic range.

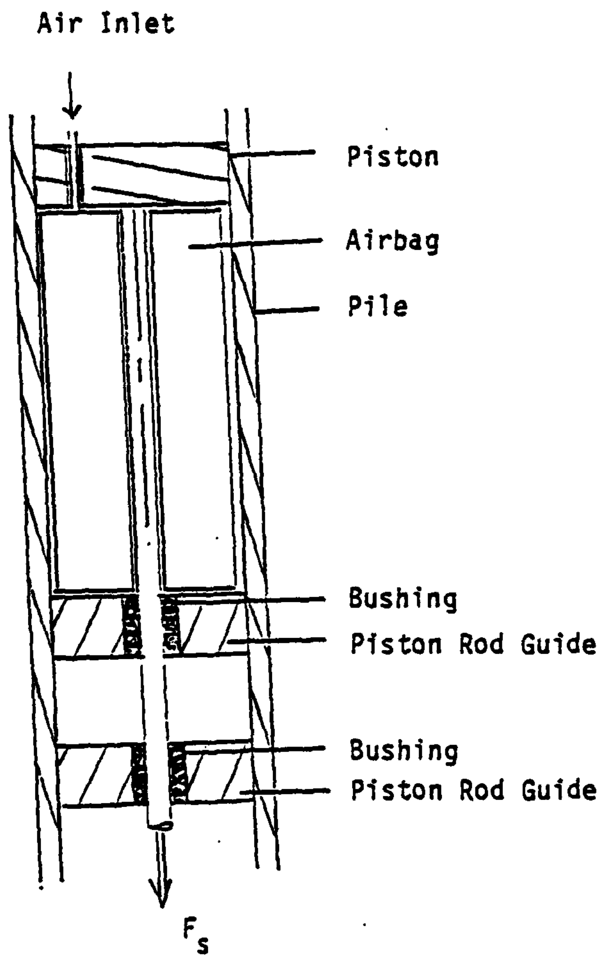

Fig. 35. The airbag "spring" concept. The doughnut shaped bag is used to seal the piston-cylinder system shown.

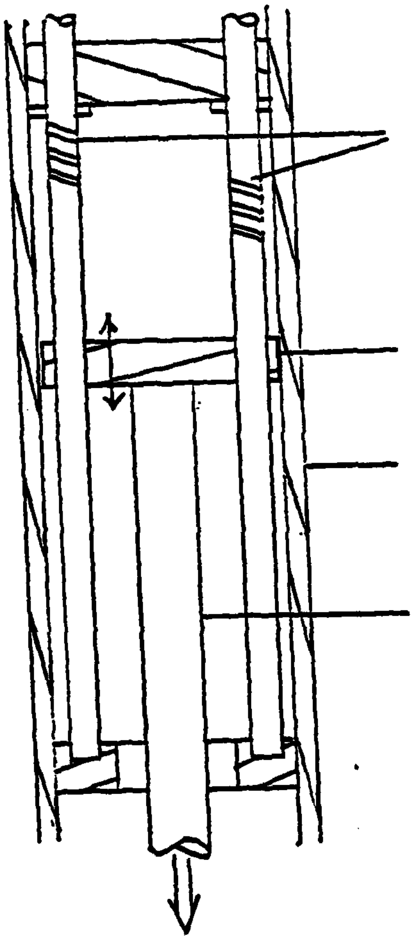

Fig. 36. Worm gear jack for prestressing an elastic spring element.

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